GAMMA RAY DOSIMETRY WITH A SCINTILLATION COUNTER

G. D. PRESTWICH AND T. H. COLVIN

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GAMMA RAY DOSIMETRY
with a
SCINTILLATION COUNTER

by

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ABSTRACT

Title: "Gamma Ray Dosimetry with a Scintillation Counter"

Authors: George Downes Prestwich and
Ted Howard Colvin

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In this paper we evaluate the worth of a scintillation counter as an instrument to measure gamma ray dosage; i.e., the energy absorption per unit mass. Data are obtained by calculations from differential pulse height spectra obtained with nearly monoergic sources in the 0.2 to 3 Mev range; and comparisons of average secondary electron energy with that theoretically expected are made. Also dosages calculated from the crystal output are compared with that obtained from an ion chamber.

It is concluded (on theoretical grounds) that organic crystals are much better suited for dosage measurements than inorganic types; and (on experimental grounds) that as the gamma ray energy is increased the finite size of the crystal causes the average secondary electron energy (and therefore the expected dosage) to decrease. This is explained by "leakage"; i.e., edge effects of the crystal. One can decrease this effect by surrounding the crystal in an air-equivalent medium such as lucite which reflects the secondary electrons back into the crystal.

Other experimental conclusions are: (a) Lucite light pipe and reflectors associated with the scintillator

have little effect on dosage. (b) Removal of photons from the beam, though an appreciable effect, can easily be computed and thus corrected. (c) Plural scattering effects in the crystals used are shown to be relatively unimportant. (d) Dosage determinations with the scintillation counter using our experimental set-up are somewhat indeterminate due to the difficulty in determining th window width of the differential discriminator. However values of dosage obtained are in reasonable agreement with those obtained from the conventional ion chamber. (e) A value of the gamma energy of radium which is a weighted average of the various energies according to abundance is experimentally determined. If meaningful it indicates that the gamma spectrum of radium is somewhat more energetic than indicated by the spectrum commonly accepted. It is felt, however, that these results are not too significant, due to the heterogeneity of the radium spectrum.

Thesis Supervisor: Robley D. Evans
Title: Professor of Physics

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I. INTRODUCTION

A. Statement of Problem and Interest Therein.

All measurements of gamma ray dosage have, for years, been based on the air ionization chamber, for it can be simply made and rather easily calibrated to read dosage in roentgens. Of course, there are many survey instruments in current use which ostensibly read dosage *rate*, but these are usually counter tubes with output connected to an RC integrating circuit so as to give a DC current roughly proportional to the intensity of the radiation incident thereon. These are usually calibrated with the heterogeneous gamma spectrum of a standard radium source and are therefore of little value in obtaining an accurate estimate of roentgen dosage for sources other than radium.

A more comprehensive treatment of the meaning of "dosage" makes the reason for the preceding statement obvious and is to be found in Section II-A-2.

Many of the usual requirements of medical and other research physics are incompatible with the inherent characteristics of ionization chambers. Small size ion chambers are desired in order that "good" geometry may

be obtained, or that a quantitative measure of activity localized in a small area, and the exact position of that small area, be obtained. However, when we try to meet the small size requirements, we find that the exposure time must be very long in order to get an accurate reading of dosage and to obtain dosage rate therefrom. For example, the small Victoreen chamber is a very convenient size, but reads 250 roentgens full scale. For the usual tracer dose in medical physics where the dosage to be measured is of the order of 10 mr/hr or less, it is clear that the length of time to obtain a reasonable scale reading is prohibitive. If one finds a chamber which has a reasonable scale, i.e., 200 mr full scale or less, the physical dimensions are apt to be ten times larger than the area to be localized.

Thus we see that a need exists for a small yet efficient instrument for dosage measurements. The use of a scintillation counter for this purpose was suggested to the authors by Dr. Gerald J. Hine of the Radioactivity Center, M.I.T., and with his advice and encouragement, this investigation was begun. The smallness of the scintillation crystal would permit good "localization"

of an activity, or its use in a "good" geometry experiment, while its density, which is many times that of air, would render much more efficient sampling of the radiation incident thereon, permitting more rapid measurements of dosage and dosage rate with small activities.

Recent authors$^{(1)}$ have stated that organic scintillators "should be relatively 'air-equivalent'" in the region above 200 Kev, i.e., the domain of most gamma emitters. We shall show that the statement is easier said than demonstrated. The meaning of the term "air-equivalence" and its significance for this problem are discussed in Section II.

B. Methods of Approach.

It would be very convenient to have a compact instrument which would cause a needle to deflect an amount proportional to the dosage rate at the instrument probe's position. The initial efforts of the authors were along this line, and led deeper and deeper into an electronic morass, until the electronic complications threatened to obscure the physical principles involved in obtaining a dosage measurement from a scintillator. At length it was rather conclusively shown that the

electronic equipment under experimentation would never be able to do the job with an error satisfactory for research work. A comprehensive evaluation of the circuitry involved is presented in Section III-A.

Therefore, in order to by-pass the electronic difficulties and investigate the physical feasibility of dosimetry with a scintillation counter, the troublesome parts of the electronic circuit were removed and replaced partly with other types of electronic equipment and partly with two human beings. The authors realize that this is a bit far afield from the original desire for a "needle deflection". However, the determinations made and results obtained are basic to the problem. We shall leave the development of electronic circuitry to the electronic experts if the experimental physical determinations prove favorable to scintillation dosimetry; the reader is referred to Section V for our conclusions. A complete discussion of the final equipment and its manner of operation is to be found in Section III-B; while the results obtained therewith are to be found in Section IV-A et seq. Before proceeding to the experimental side, however, we must review a considerable amount of theory regarding the gamma ray interactions with matter.

II. THEORETICAL BASIS FOR THE PROBLEM

A. Basic Considerations.

1. Effect of Gamma Rays on Matter.

In considering a problem involving the "dosage" due to gamma radiation, it is first necessary to review in general the mechanisms by which gammas interact with matter and how these interactions pertain in particular to the problem at hand. First of all, what is "dosage"?

Physically speaking, the end result of all gamma interactions in matter is ionization of the atoms therein. Physiologically speaking, the ionization of matter is a disruption of the constituents of the matter and in it is contained the danger to health; in it is the manifestation of "dose". This ionization requires energy supply, and the gamma beam is the source thereof. The production of ion-pairs is not, however, in one-to-one correspondence with gamma-electron collisions as one might naively think. Indeed, a single gamma-electron collision produces one ion-pair, but the electron member of the pair has a large energy, on the average roughly half that of the incident gamma

ray, or in the domain of thousands of electron-volts. Since the energy required for the production of an ion-pair in material such as air or tissue is of the order of tens of electron-volts, the energetic electron resulting from a single gamma-electron collision can and does produce many other ion-pairs, until its energy is fully expended. It is by this process, the step-by-step dissipation of the energy of the "secondary electrons" as the energetic fellows are termed, that the energy absorbed from the gamma ray beam is translated into ionization in the material.

2. The Roentgen.

The "roentgen" is the unit of dosage, and expresses the measure of gamma ray effect on matter in terms of the ionization discussed above. A roentgen is defined(3) as "that quantity of x- or gamma radiation such that the associated corpuscular emission per 0.001293 gm of air produces, in air, ions carrying one electrostatic unit of charge of electricity of either sign".

The corpuscular emissions referred to in the definition are the "secondary electrons" of our terminology. The quantity of air is 1 cc of dry air at 0° C and 760 mm Hg. Since 1 esu = 2.083×10^9 ion-pairs, 1 roentgen produces 1.61×10^{12} ion-pairs per gram of air. If an

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average of 32.5 e.v. is expended (4,5) then 1 r corresponds to 5.24×10^7 Mev/gm of air. We shall have occasion to refer to this number later.

It should be noted that dosage is independent of time, due to the definition of the dosage unit of roentgens; therefore gamma ray dosage rates are given in roentgens/unit time; e.g., mr/hr = milliroentgens per hour. Also of importance is the concept of dosage rate as a measure of ionization intensity and not a measure of gamma intensity, for the reasons discussed above.

3. Production of Secondary Electrons.

The first process encountered then in the production of dosage by gamma radiation is the production of the secondary electrons. Here we encounter the well-known threefold process of importance in this problem by which gamma rays interact with electrons in matter: (a) Compton collisions, (b) photoelectric effect and (c) pair production. We have referred above to gamma-electron collisions, a term which is descriptive but not essentially true except for (a). In the Compton process, the gamma photon may be considered as a relativistic "cue ball" colliding with a free object ball at rest, with the usual consequences of billiard

ball collisions; i.e., transfer of energy with conservation of total mass-energy and momentum. In the photo-effect, the gamma may be considered as being swallowed whole by an atom, which then usually relieves itself by disgorging an electron with energy equal to that of the gamma ray minus the electronic binding energy. In pair production, an interaction explainable only in quantum terms occurs, in which a gamma ray, finding itself in the intense fields in the immediate vicinity of a nucleus, becomes so confused that it commits quantum suicide and is reincarnated as a positron-electron pair, which share an amount of energy equal to that of the gamma ray minus the rest energy of these particles (1.02 Mev).

All three of the above effects can and will occur in all materials, and (except for pair production with its mass-energy threshold of $2 m_0c^2 = 1.02$ Mev) for any energy gamma ray. Happily, it frequently happens that one effect predominates to the near exclusion of the others, when one considers a particular material and a particular range of gamma energies. For example, for low gamma energies, in the domain less than 100 Kev for materials of moderate to high atomic number, the photoelectric effect predominates. For high gamma

energies, say above 3 Mev, and for high atomic number material, pair production predominates. Finally, for the great middle range of gamma energies and for materials of low atomic number such as air and tissue, the Compton effect predominates.

4. Secondary Electron Interactions.

Having seen in general how the energetic secondary electrons are produced, let us see how they produce the ionization, i.e., the real "dosage". At this point comes the basic stumbling block in our problem. In air, (that is, in the medium for which dosage units are defined) the energy of the secondary electrons is converted into ionization by a series of "soft billiard ball" collisions. That is, the cue ball (secondary electron) loses a little bit of its energy in each ionizing collision with a molecule, until it is all gone, after which we have a medium filled with ions, positive or negative, floating around. In an ionization chamber, the collecting electrodes then remove the charged particles. If no electrodes are present, recombination very shortly occurs. The total number of ion-pairs is proportional to the energy of the secondary electrons, since as pointed out above, the energy required for production of an ion-pair is roughly constant at about 32.5 e.v./ion-pair.

For this reason, one can make an air ionization chamber which collects the ion-pairs formed, measures their total charge and therefore has a measure of dosage.

In a scintillation crystal, however, one does not collect any charge and measure it. Indeed, the mechanism of the scintillator is complicated and has not been fully investigated (6). Suffice it to say that the ionization which secondary electrons produce in the crystal causes a flash of visible light (or in the near ultraviolet range), which, in anthracene, has been shown to produce a photomultiplier voltage pulse proportional in amplitude to the energy of the secondary electron initiating it (7,8). Thus we see that the final effect of gamma irradiation of a scintillator is entirely different from the effect in air, in terms of which dosage is defined. Nevertheless, if we can obtain a measure of the light intensity by the voltage pulses it produces, we have a measure of the rate of energy absorption from the gamma ray into the secondary electrons. If then the energy spectrum of the secondary electrons produced in the scintillator is the same as, or approximates the energy spectrum of the secondary electrons produced in air, we have a measure of the "dosage" which the same gamma intensity would produce

on a cc of air at the scintillator's position, for the ionization produced in air is *also* proportional to secondary electron energy. There are, of course, a few complications, which will be considered in due course of this paper.

We shall see later how one goes about measuring the number and amplitude of the pulses due to the light flashes and obtains a measure of dosage therefrom. Before that, there is a criterion to be applied which determines the type of scintillator appropriate for the stated purpose.

B. Average Energy of the Secondary Electrons.

1. Relation of Average Energy of Secondary Electrons to Dosage.

Since the energy of the secondary electrons produced by the photons in the scintillator is related to the energy absorbed from the gamma beam and thus to the dosage, it is of interest to calculate the variation in the average secondary electron energy produced in a given material by the variation of gamma energy. Because dosage is defined in terms of charge produced in air, we will determine this variation for air, anthracene, and sodium iodide. The choice of anthracene

and sodium iodide crystals for this determination is dictated by the fact that these are the two crystals most used in scintillation counting today; anthracene, the organic type; sodium iodide, the inorganic type. Anthracene being a hydrocarbon, one would expect that it would be "air-equivalent"; that is to say, over the range from 0.1 Mev to 10 Mev one would expect that the Compton effect greatly predominates over the photoelectric effect and pair production in materials of low atomic number. For such a condition, it will be shown that the average secondary electron energies are identical for the materials satisfying it. Conversely, since sodium iodide is inorganic and contains elements of moderate atomic number, one would expect such a crystal to be "air-equivalent" only over a much reduced range or not at all. It is anticipated that sodium iodide will be inherently unsuitable for gamma ray dosimetry because of its lack of "air-equivalence".

2. Formula for Average Energy of Secondary Electrons.

How then does one find the average energy of the secondary electrons? We shall consider first that the gamma energy is a continuous variable, producing secondary electrons in a small thickness. From such a determination we shall later show how an effective average secondary

electron energy can be obtained for a particular source and finite crystal thickness.

Let E_γ = gamma ray energy in Mev.

n = number of photons/cm^2-sec of energy E_γ incident on material considered.

A = effective area of incidence (cm^2).

${}_e\sigma$ = total Compton cross section in cm^2/electron.

${}_e\sigma_a$ = Compton absorption cross section in cm^2/electron.

σ = Compton linear attenuation coefficient in cm^{-1}.

σ_a = Compton linear absorption coefficient in cm^{-1}.

τ = photoelectric linear attenuation coefficient in cm^{-1}.

K = pair production linear attenuation coefficient in cm^{-1}.

μ = total linear attenuation coefficient in cm^{-1}

$= \sigma + \tau + K$.

μ_a = linear absorption coefficient in cm^{-1}

$= \sigma_a + \tau + K$.

W = binding energy of "K" electron.

Then the energy/sec absorbed in a thickness dx (10) = the total energy/sec of the secondary electrons = E_T:

$$E_T = nAdx\left[\sigma_a E_\gamma + \tau(E_\gamma - W) + \kappa(E_\gamma - 2m_oc^2)\right] \quad \text{(II-B-1)}$$

where $2m_oc^2$ = energy equivalent of 2 electron rest masses. Let the number of secondary electrons produced per sec = N; then

$$N = nAdx(\sigma + \tau + \kappa) = \mu nAdx \quad \text{(II-B-2)}$$

Therefore the average electron energy is

$$E_{AV} = \frac{E_T}{N} = \frac{\sigma_a E_\gamma + \tau(E_\gamma - W) + \kappa(E_\gamma - 1.02\ \text{Mev})}{\sigma + \tau + \kappa} \quad \text{(II-B-3)}$$

It is of interest to consider the magnitude of W for the materials of interest, remembering our minimum E_γ = 0.1 Mev.

Table II-B-1

Element	W
H	Negligible
C	Negligible
N	Negligible
O	Negligible
Na	1.07 Kev
I	33.2 Kev

3. Calculation of Attenuation and Absorption Coefficients.

In order now to compute E_{AV} as a function of E_γ

for each material, one must first find or compute values of σ, σ_a, τ, κ. See Appendix A for these computations and the results.

4. Comments on Computed Secondary Electron Average Energy.

Now having the required attenuation and absorption coefficients we can return to formula (II-B-1) and compute E_{AV} for E_γ in the range 0.1 Mev to 10 Mev. The results of these computations are displayed in Figure 1. Figure A-1, a plot of computed μ over the range of interest is included for use with later theory requirements. Here we see that anthracene is theoretically truly "air-equivalent" from 0.2 Mev to 8 Mev, while sodium iodide deviates widely from the air curve for $E_\gamma < 1$ Mev. We note that even down to 0.1 Mev, anthracene is theoretically substantially "air-equivalent".

From the above theoretical calculation, it was decided that sodium iodide and other inorganic crystals had average electron energies far greater than air for $E_\gamma < 1$ Mev, since the secondary electron energy for photoelectric absorption is $E_\gamma - W$ which is far greater than $\frac{\sigma_a}{\sigma}E_\gamma$ at low energies, (for $E_\gamma = 0.1$ Mev, $\frac{\sigma_a}{\sigma} = 0.14$) and would thus give too great a measure of dosage. Thus the remainder of our measurements and theory is based on

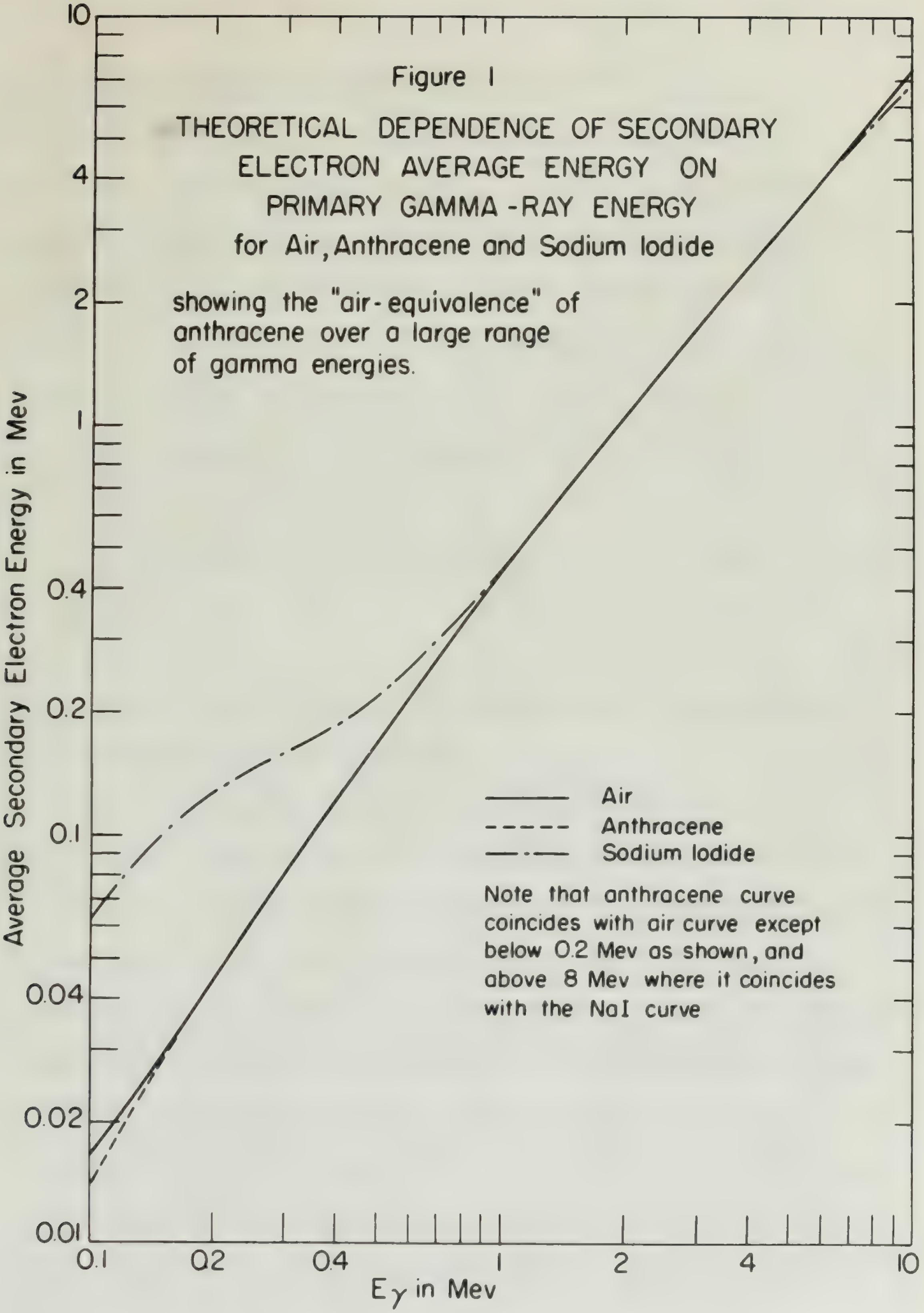


Figure 1

THEORETICAL DEPENDENCE OF SECONDARY ELECTRON AVERAGE ENERGY ON PRIMARY GAMMA-RAY ENERGY for Air, Anthracene and Sodium Iodide

showing the "air-equivalence" of anthracene over a large range of gamma energies.

Note that anthracene curve coincides with air curve except below 0.2 Mev as shown, and above 8 Mev where it coincides with the NaI curve

the use of anthracene as a scintillator.

Since we will be dealing with anthracene from here on, and with 0.1 Mev $< E_\gamma <$ 8 Mev, we can make an obvious simplification of formulas (II-B-1) and (II-B-3). For carbon and hydrogen, W is negligible; also no pair production is observable. Therefore, these equations become

$$E_T = nAdx(\sigma_a + \tau)E_\gamma = n\mu_a E_\gamma Adx \qquad \text{(II-B-4)}$$

$$E_{AV} = \frac{\sigma_a E_\gamma + \tau E_\gamma}{\sigma + \tau} = \frac{\mu_a}{\mu} E_\gamma \qquad \text{(II-B-5)}$$

C. Theoretical Treatment of Quantities to be Measured in the Scintillation Crystal.

1. Average Electron Energy Significance.

We have seen that the absorption of energy from the gamma beam in the crystal results in the production of secondary electrons. We have also seen that each such electron gives a pulse of light which produces a voltage pulse proportional in amplitude to the electron energy. As will be shown in Section IV-A we can then obtain (1) a quantity expressing the total amount of energy per unit time received by the electrons in the crystal from the gamma ray, i.e., the rate of energy absorption

in the crystal; and (2) a measure of the total number of electrons energized per unit time. Ostensibly, dividing (1) by (2) should give us a measure of the secondary electron average energy, for comparison with the theoretical curve obtained in B above (Fig. 1); while (1), since it represents the energy absorbed from the gamma beam, should be a measure of dosage and related to the "air-dose" in roentgens. That these conclusions are not quite so simple and direct but subject to modification in theory, disregarding experimental difficulties, is the purpose of this and the following divisions in Section II. (Authors' note: Immediately after the following theory was evolved, part I of a paper by Whitcher (17) was published, dealing with a very similar situation in liquids. Unfortunately, part II of the paper is to contain the calculations of interest and will not be available until after May 16, 1952. Attention is invited thereto when available.)

C. Relation between E_{AV} and Dosage.

To begin with, let us assume that each gamma photon has only one interaction in the crystal. The consequences of multiple interactions are considered later in Section II-D. Now from Section II-B we have the equations

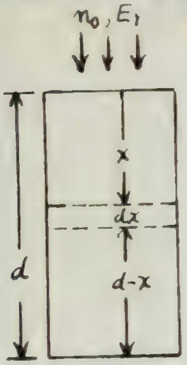
Total secondary electron energy/unit time produced in a thickness dx =

$$E_T = n\mu_a E_\gamma A dx \qquad \text{(II-B-4)}$$

Total number of secondary electrons produced/unit time in dx =

$$N = n\mu A dx \qquad \text{(II-B-2)}$$

For the moment we shall treat E_γ as single valued; i.e., a monoenergic source is being used:



If the crystal is very thin, then n is constant and = n_o, the number of photons/cm^2-sec incident on crystal face. Obviously for this case,

$$E_T = n_o \mu_a E_\gamma A d \qquad \text{(II-C-1)}$$

$$\text{and } N = n_o \mu A d \qquad \text{(II-C-2)}$$

Here $E_{AV} = \frac{\mu_a}{\mu} E_\gamma$ again and agreement should be obtained with the curve of Section II-B.

Also, suppose that one used two different monoergic sources E_{γ_1} and E_{γ_2}, for which there were the corresponding quantities n_{o_1}, μ_1, μ_{a_1} and n_{o_2}, μ_2, μ_{a_2}. If E_T is truly a measure of roentgen dosage rate as would be recorded by an ion chamber as rates R_1 and R_2, say, then the ratio

$$\frac{R_1}{R_2} = \frac{n_{o_1} \mu_{a_1} E_{\gamma_1}}{n_{o_2} \mu_{a_2} E_{\gamma_2}} \qquad \text{(II-C-3)}$$

Such a ratio holds strictly true for the "air-wall" ion chamber according to Evans (10) and Rossi and Staub(27)

since dose rate $R = \frac{nE_\gamma \mu_a}{\rho}$ in Mev/min-gm air; and if we can satisfy the assumptions made to date then

$$\frac{E_{T_1}}{E_{T_2}} = \frac{R_1}{R_2} \qquad \text{(II-C-4)}$$

E. Removal of Photons.

The difficulty, however, lies in the assumptions. Let us first consider the effect of crystal thickness. The very advantage of the scintillation crystal is its increased efficiency; that is to say, it has many more gamma interactions than an equivalent volume of air. But if we increase the number of interactions, then n is not constant and equal to n_o but follows the usual "good" geometry attenuation law

$$n = n_o e^{-\mu x}$$

Therefore, for a crystal of thickness d,

$$E_T = \int_o^d n_o e^{-\mu x} \mu_a E_\gamma A dx$$

$$= n_o \mu_a E_\gamma A d \left(\frac{1 - e^{-\mu d}}{\mu d} \right) \qquad \text{(II-C-5)}$$

and

$$N = n_o \mu A \int_o^d e^{-\mu x} dx$$

$$N = n_o \mu A d \left(\frac{1 - e^{-\mu d}}{\mu d} \right) \qquad \text{(II-C-6)}$$

These equations reduce to (II-C-1) and (II-C-2) of course in the limit of small μd; i.e., for d small compared to $\frac{1}{\mu}$, the mean free path for scattering.

We note that $E_{AV} = \frac{E_T}{N}$ is unchanged by this correction and still equals $\frac{\mu_a}{\mu} E_\gamma$.

However the ratio $\frac{E_{T_1}}{E_{T_2}} = \frac{R_1}{R_2}$ is no longer strictly true if μd is not $<< 1$. That is

$$\frac{E_{T_1}}{E_{T_2}} = \frac{n_{o_1} \mu_{a_1} E_{\gamma_1} (1 - e^{-\mu_1 d})/\mu_1 d}{n_{o_2} \mu_{a_2} E_{\gamma_2} (1 - e^{-\mu_2 d})/\mu_2 d} \qquad \text{(II-C-7)}$$

and depending on crystal thickness and E_γ, we would not theoretically expect that our measurements would give the same dosage ratio as an air-wall ion chamber. The magnitudes of these corrections will be presented later and an evaluation of the expectation values obtained.

3. Non-monoergicity.

The second assumption, that of monoergic E_γ, is readily removable. We shall generalize our notation a bit: Let p_{ji} = percent abundance of i^{th} gamma ray from j^{th} source.

$E_{\gamma_{ji}}$ = energy of i^{th} gamma ray from j^{th} source.

μ_{ji} = total linear attenuation coefficient corresponding to $E_{\gamma_{ji}}$.

$\mu_{a_{ji}}$ = linear absorption coefficient corresponding to $E_{\gamma_{ji}}$.

n_{o_j} = total number of photons/cm^2-sec incident from j^{th} source.

Then $n_{o_{ji}} = \dfrac{n_{o_j} p_{ji}}{\sum_i p_{ji}}$ = photons/cm^2-sec of i^{th} energy incident, (II-C-8)

and define $\overline{E}_{\gamma_j} = \sum_i (p_{ji} E_{\gamma_{ji}}) / \sum_i p_{ji}$ (II-C-9)

(For example the two γ's from Co^{60} have abundances of 100 percent each and energies of 1.17, 1.33 Mev.) If Co^{60} is j^{th} source considered, then

$$n_{o_{j1}} = \frac{n_{o_j}}{2};\ n_{o_{j2}} = \frac{n_{o_j}}{2};\ \overline{E}_{\gamma_j} = \frac{1.17 + 1.33}{1 + 1} = 1.25 \text{ Mev.}$$

Then for the i^{th} γ from the j^{th} source,

$$dE_{T_{ji}} = n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}} A e^{-\mu_{ji} x} dx$$

$$dN_{ji} = n_{o_{ji}} \mu_{ji} A e^{-\mu_{ji} x} dx$$

and for the aggregate beam from j^{th} source,

$$dE_{T_j} = \sum_i n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}} A e^{-\mu_{ji} x} dx$$

$$dN_j = \sum_i n_{o_{ji}} \mu_{ji} A e^{-\mu_{ji} x} dx$$

Again integrating over the crystal thickness we obtain:

$$E_{Tj} = \sum_i n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}} Ad \left(\frac{1 - e^{-\mu_{ji} d}}{\mu_{ji} d}\right) \qquad \text{(II-C-10)}$$

$$N_j = \sum_i n_{o_{ji}} \mu_{ji} Ad \left(\frac{1 - e^{-\mu_{ji} d}}{\mu_{ji} d}\right) \qquad \text{(II-C-11)}$$

$$\text{whence } E_{AV_j} = \frac{\sum_i n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}} \left(\frac{1 - e^{-\mu_{ji} d}}{\mu_{ji} d}\right)}{\sum_i n_{o_{ji}} \mu_{ji} \left(\frac{1 - e^{-\mu_{ji} d}}{\mu_{ji} d}\right)} \qquad \text{(II-C-12)}$$

$$\text{and } \frac{E_{T_j}}{E_{T_k}} = \frac{\sum_i n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}} \left(\frac{1 - e^{-\mu_{ji} d}}{\mu_{ji} d}\right)}{\sum_i n_{o_{ki}} E_{\gamma_{ki}} \mu_{a_{ki}} \left(\frac{1 - e^{-\mu_{ki} d}}{\mu_{ki} d}\right)} \qquad \text{(II-C-13)}$$

We now see that the correction for non-monoergicity results in several changes in procedure.

(a) Eq. (II-C-12) can be written:

$$E_{AV_j} = \frac{\sum_i n_{o_{ji}} E_{\gamma_{ji}} \frac{\mu_{a_{ji}}}{\mu_{ji}} \left(1 - e^{-\mu_{ji} d}\right)}{\sum_i n_{o_{ji}} \left(1 - e^{-\mu_{ji} d}\right)}$$

There we see that $E_{\gamma_{ji}} \frac{\mu_{a_{ji}}}{\mu_{ji}} = E_{AV_{ji}}$, the value which would be picked off the curve of Figure 1, corresponds to $E_{\gamma_{ji}}$.

Therefore, in order to evaluate the intrinsic equivalence of anthracene to air by the "most nearly correct" theory available to date, we must compute E_{AV_j} for the j^{th} source from the curve, and compare it to the measured value. The value obtained will depend on crystal thickness d; we shall see presently how violently. Also, one can compute a "partially corrected" E_{AV_j} by omitting the terms in $\mu_{ji}d$; which also gives an idea of the effectiveness of crystal thickness attenuation. As we shall see in Section IV, the experimental results may then be compared with the "totally corrected" and "partially corrected" values. The theoretical values are presented in tabular form in Table (II-C-1) and are presented in graphical form along with the experimental results in Section IV, Figures 7 and 8.

TABLE II-C-1

		E_{AV}	E_{AV} (totally corrected)	
Source	$\overline{E}_{\gamma}$ [x]	(partially corrected)	d = 6 mm	d = 20 mm
Hg^{203}	280 Kev	72.1 Kev	72.1 Kev	72.1 Kev
Cs^{134}	698 Kev	271.5 Kev	265.9 Kev	266.5 Kev
Co^{60}	1.25 Mev	586. Kev	584. Kev	584. Kev
Na^{24}	2.07 Mev	1.109 Mev	1.028 Mev	1.037 Mev

[x] From formula (II-C-9).

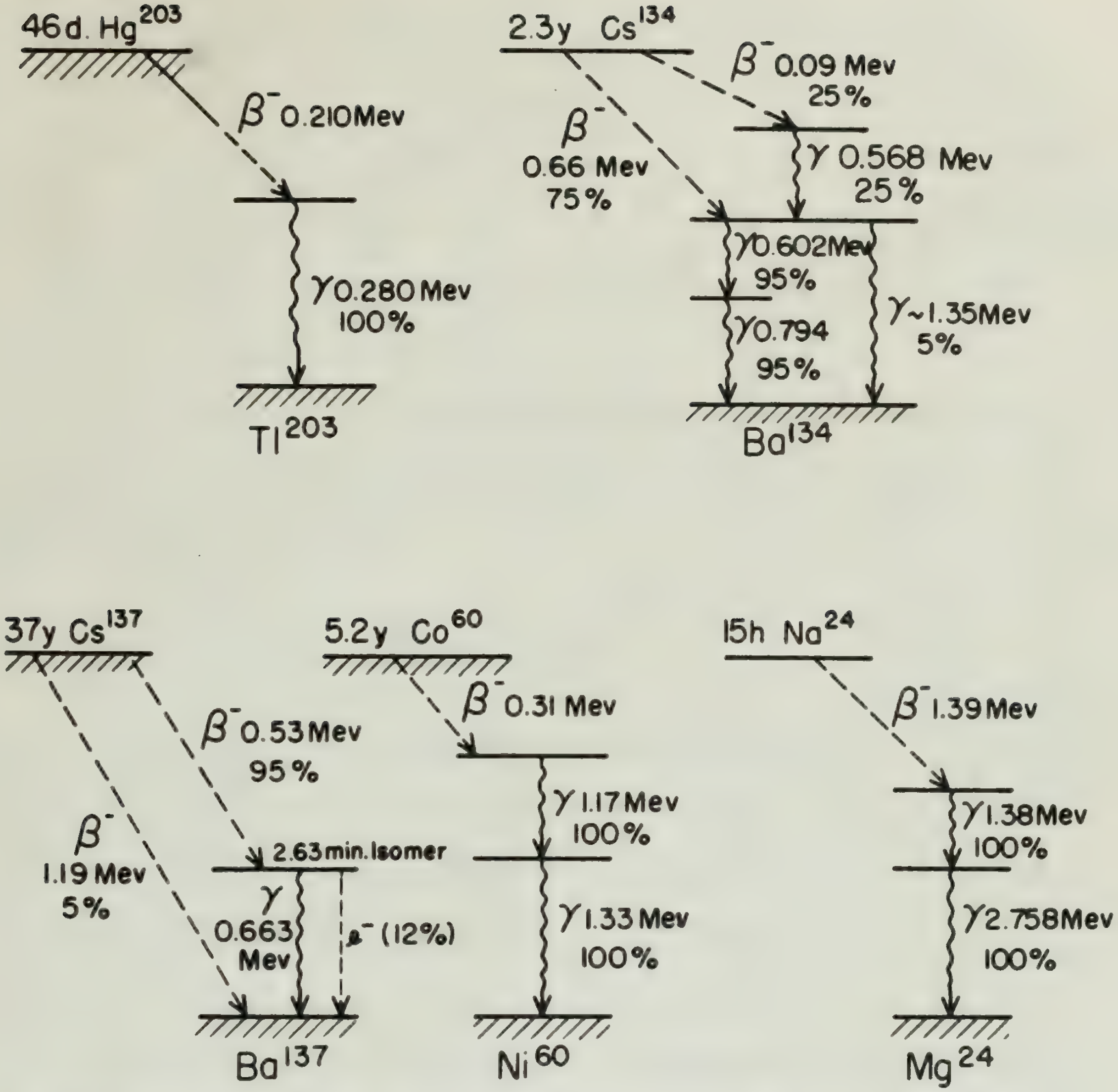
From this table we see that the correction for crystal thickness causes only slight changes (<2 percent) in all but the sodium source, whose γ energies are separated widely. Figure 2 shows the decay schemes and necessary details for the computations involved. Figure A-1 (Appendix) furnishes the values of μ required. It is interesting to note how much more important crystal thickness would have been for the sodium iodide crystal with its far larger values of μ and rapid increase at low energy due to photo-effect.

(b) Returning now to our ratio of $\frac{E_{T_j}}{E_{T_k}}$, we see that if $\mu d \ll 1$ then

$$\frac{E_{T_j}}{E_{T_k}} = \frac{\sum_i n_{o_{ji}} E_{\gamma_{ji}} \mu_{a_{ji}}}{\sum_i n_{o_{ki}} E_{\gamma_{ki}} \mu_{a_{ki}}} \text{ and } \frac{E_{T_j}}{E_{T_k}} = \frac{R_j}{R_k}$$

rigorously since the correction for non-monoergicity applies equally well to the ion-chamber! However, for μd not $\ll 1$, we will again have a difference in the observed ratio, and again, in theory alone, would not expect our measured dosage ratios to agree with those from the ion-chamber.

Accordingly, if the correction for μd is appreciable and our assumptions are reasonably correct, then our problem would seem insoluble. Hence, one must consider the theoretical magnitude of the expected deviation due to crystal thickness.



Note: Level separations schematic only; no energy scaling attempted.

Figure 2

ENERGY LEVEL DIAGRAMS FOR RADIO NUCLIDES USED IN THIS INVESTIGATION.

(Reference: "Nuclear Data", Nat'l. Bureau of Standards Circ. 499, 1951)

A table of the correction factors $\left(\frac{1 - e^{-\mu d}}{\mu d}\right)$ is of value, for if they differ for each source by only a small amount, one might be able to assume a median value of the correction such that the true error over a given range would theoretically be expected to be less than a certain maximum within the limits of experimental error.

Considering average values of E_γ for the sources considered, except for the widely spread Na^{24} energies we obtain Table II-C-2.

TABLE II-C-2

d(mm)	Source	$\mu(cm^{-1})$	$1 - e^{-\mu d}$	$\frac{1 - e^{-\mu d}}{\mu d}$
6	Hg^{203}	0.143	0.082	0.958
6	Cs^{134}	0.098	0.0571	0.971
6	Co^{60}	0.074	0.0432	0.974
6	Na^{24} (1.38)	0.070	0.0412	0.981
6	Na^{24} (2.76)	0.0482	0.0284	0.983
20	Hg^{203}	0.143	0.249	0.871
20	Cs^{134}	0.098	0.178	0.909
20	Co^{60}	0.074	0.1377	0.931
20	Na^{24} (1.38)	0.070	0.1303	0.933
20	Na^{24} (2.76)	0.0482	0.0915	0.953

From Table II-C-2, we see that it is possible to assume a "calibration factor" in the middle of the range of values of the factor$\left(\frac{1 - e^{-\mu d}}{\mu d}\right)$ such that a certain percent accuracy can be expected. That is to say, if all experimental errors were zero, then if the dosage readings were "calibrated" by dividing by the median $\left(\frac{1 - e^{-\mu d}}{\mu d}\right)$ factor, we would expect a certain percentage error for the several sources based solely on the theory developed to date:

(a) for the 6 mm crystal; assuming a calibration factor = 0.970, we see that the maximum error incurred for this range is about 1.4 percent.

(b) for the 20 mm crystal; assuming a calibration factor of 0.912 we can cover the whole range with a maximum error of 4.5 percent; or using 0.931 and eliminating the low end of the range we can obtain a maximum error of 2.3 percent.

The value or lack thereof of these considerations will be demonstrated in Section IV where theory and experimental results are compared.

Before leaving the theoretical development, let us consider two effects briefly mentioned above; the effect of plural scattering, and the effect of the leakage of energetic electrons from the confines of the crystal prior to expending all their energy into light output. These

cannot be handled rigorously in an analytic manner, but a qualitative idea of their importance can be obtained by making some rather gross approximations. Sections D and E do this job in so far as the authors are able.

D. Plural Scattering Correction Approximation.

1. Effects of Plural Scattering.

The assumption has been made in the preceding theory that each photon suffers but one collision in the crystal. In possible justification of this assumption, let us examine more closely what it involves. To begin with, if a photon suffered another collision in the crystal, thus producing a second energetic electron and a corresponding output of light scintillation, it is clear that the resultant light from the second collision would not be a separate light pulse. The longest length of time possible between the two collisions in the thickest crystal is of the order of $\frac{2\text{ cm}}{3 \times 10^{10}\text{ cm/sec}} \sim 10^{-10}$ seconds while the resolving time of anthracene is $\sim 10^{-8}$ sec(8). Therefore the light from the second collision increases the intensity of the light scintillation due to the first collision, and the photomultiplier contributes a pulse equal to that which it would have produced had the gamma lost in one collision all the energy that it lost in two collisions. Thus second collisions

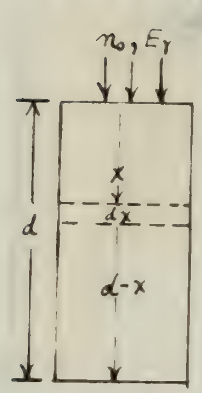
do not increase the total counting rate but will increase the total energy measured and thus increase the measured average energy of the secondary electrons and the computed dosage over that which would be expected from the theory developed to date. Note that if it should prove to be of importance only for the Hg^{203} and the 20 mm crystal, then the low correction factor for this case in Table II-C-2 would be effectively increased and the range of error assuming a "calibration" factor of somewhat greater than 0.912, say 0.931, could be reduced (refer page 28). As will be seen in Section IV, an increase in average electron energy was noted as the crystal thickness increased; it is the purpose of this section to show whether the increase could or could not be due to second gamma collisions and whether it must be explained by another phenomenon; for instance, the leakage of energetic electrons from the crystal.

2. Analysis of Plural Scattering.

We shall assume some conditions which should be nearly optimum for second collisions to contribute appreciably to the energy absorption:

(a) Let n_o = number of photons/cm^2-sec incident on crystal, of area A.

E_γ = their energy.



μ = the linear attenuation coefficient at this E_γ.

(b) Assume all primary collisions are such that the photons still go nearly in the forward direction.

(c) Assume photons still have energy E_γ and μ does not change.

Then the number of degraded photons produced in a thickness dx is equal to the number of electrons produced in $dx = n\mu A dx$ from formula (II-B-2). But $n = n_o e^{-\mu x}$, therefore the number of degraded photons produced in dx is $n' = n_o e^{-\mu x}\mu A dx$. Of these degraded photons, we know that $e^{-\mu(d - x)}$ of them will not have a collision between x and d, and therefore the fraction of the degraded photons which have a collision between x and d is $\left[1 - e^{-\mu(d - x)}\right]$. These are the photons which suffer at least two collisions in the crystal. Accordingly, the total number of photons which suffer at least two collisions in the crystal is $\int_o^d n'\left[1 - e^{-\mu(d - x)}\right] = n_o \mu A \int_o^d e^{-\mu x}(1 - e^{-\mu(d - x)})dx$ and the fractional number of incident photons which suffer at least two collisions, is

$$f = \mu \int_o^d (e^{-\mu x} - e^{-\mu d})dx$$

$$f = \mu \left[\int_0^d e^{-\mu x} dx - e^{-\mu d} \int_0^d dx \right]$$

$$f = (1 - e^{-\mu d}) - \mu d e^{-\mu d} \qquad \text{(II-D-1)}$$

3. Conclusions Concerning Plural Scattering.

Now let us consider the energy for which μ is largest, i.e., $E_\gamma = 0.280$ Mev for Hg^{203}, with $\mu = 0.143\ cm^{-1}$, and the longest crystal used, i.e., $d = 2$ cm. This will give us the largest f which we will have to consider, since $\mu < 0.10\ cm^{-1}$ for all other sources used. For this case, under these assumptions, the fraction of all incident photons which suffer two collisions in the crystal is

$$f = (1 - e^{-0.286}) - (0.286)e^{-0.286}$$
$$= 0.249 - 0.215 = 0.034 = 3.4 \text{ percent.}$$

But we have chosen what we hope to be optimum assumptions for second collisions contributing to the energy absorption observed; viz:

(a) If the degraded photons do not (as is the case for some 30 percent of them according to Davisson(9)) go nearly in the forward direction and (as is actually the case for most of them) their energy is less because of the additional amount given to the electrons in the primary collision, then μ is greater; but from our geometry it is seen that d', the "in-crystal" distance remaining, is

decreasing rapidly with increasing angle from the original direction; thus the product $\mu d'$ is nearly constant, and equal to μd, so f would not be materially affected.

(b) For those degraded photons which do not go nearly in the forward direction, since, as above, their energy is materially less than E_γ, the additional energy they could contribute in a second collision is less than they could have contributed in the primary collision, and thus the $f = 3.4$ percent would be greater than the actual percent increase in the total energy due to second collisions.

4. Justification of Analysis.

The true value of the percent increase in secondary electron energy due to second collisions would be extremely difficult to compute, if not impossible at the present stage of theoretical progress in the field of plural scattering, since we are concerned with a medium of small volume. It is felt that the above approximate analysis under gross assumptions provides a suitable overestimate of the increase in average and total secondary electron energy due to second collisions in the case of Hg^{203} radiation incident on the thick crystal, such that the true increase for this case is of the order of 3 percent or less. For the higher energy radiations for which μ decreases to $<0.1\ cm^{-1}$, and for the thin (6 mm) crystal, the effect of second collisions

is therefore clearly inconsequential, and for the limiting case considered, the effect is of such magnitude that consideration of it is problematical.

E. Secondary Electron Leakage.

1. Analysis.

The final factor to be considered in the physical theory applicable to the problem is due to the magnitude of the crystal dimensions in comparison to the maximum range of energetic electrons in anthracene. A few representative values applicable here are calculated from Goodman(11):

TABLE II-E-1

E(electron)	Maximum Range in Anthracene
145 Kev	0.15 millimeters
500 Kev	1.28 millimeters
1000 Kev	3.44 millimeters
1500 Kev	6.20 millimeters
2000 Kev	7.6 millimeters
2500 Kev	9.8 millimeters
2750 Kev	11.0 millimeters

The maximum energy obtainable by the electrons by

Compton collisions is given by the well-known formula(18)

$$E_{max} = \frac{E_{\gamma}}{1 + \frac{0.51}{2E_{\gamma}}} \qquad \text{(II-E-1)}$$

The maximum energies of secondary electrons from the various sources are:

TABLE II-E-2

Source	$E_{\gamma\ max}$	E_{max} (secondary electron)
Hg^{203}	280 Kev	146 Kev
Cs^{134}	794 Kev^{x}	600 Kev
Co^{60}	1.33 Mev	1.115 Mev
Na^{24}	2.76 Mev	2.525 Mev

$^{x}Cs^{134}$ has a 1.35 Mev gamma ray but of only 5 percent abundance.

Comparison of these two tables with the dimensions of the two crystals brings out a few interesting points.

(a) 6 mm crystal - cross section is a circle 30 mm in diameter. For this case, the minimum distance of travel for the secondary electrons is forward, which is the direction of the most energetic ones (head-on collision type). Since the electrons are produced all through the crystal, it is obvious that for the cobalt source and higher energies, an appreciable percentage of energetic electrons

will pass out of the scintillator before expending all their energy in light production, such percentage increasing with energy.

(b) 20 mm crystal - cross section is a rectangle 10 mm by 20 mm. For this case the forward direction is the longest dimension of the crystal, and if we consider first only those electrons in the forward direction, then the leakage described above should only be important for the highest energy, i.e., Na^{24}, and should be less than for the 6 mm crystal. However, this crystal has a narrow horizontal dimension, such that many electrons not quite in the forward direction, but enough forward that they have considerable energy, will leak out the side faces before contributing all their energy to light. This is enhanced by the fact that the gamma beam is not truly parallel, due to the finite source-to-crystal distance (which was kept at least 10 times crystal dimensions) but diverges slightly, such that the most energetic electrons if produced near a side face, would be "aimed" to go out of the crystal. This effect would be negligible in the thin crystal due to its cross section.

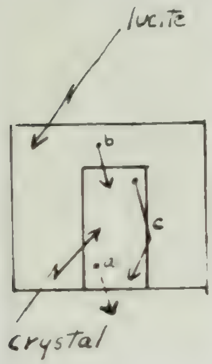
2. Effect of Leakage.

Since the effects mentioned above would tend to decrease the energy converted into light and measured, one

would expect a decrease below the theoretical values both of E_{AV} and E_T ("dosage") due to this cause, in opposition to the increase expected due to plural scattering (Section II-D). Further, it would be expected to have more effect in the thin crystal than the thick, and to be of most concern for the higher energy gamma rays.

3. Solution to Leakage Problem.

A theoretical configuration to correct some of these ills suggested itself near the end of our experimentation. If one enclosed the crystal in a box of material of about the same density and composition of anthracene, say lucite for example, two effects could occur:



(a) and (b) On the average, for a number of electrons which leak out of the bottom of the crystal (a) producing a light pulse indicating an energy smaller than it actually had, there is a corresponding number (b) leaking in from the lucite top and producing a light pulse corresponding to the rest of the energy. Note that these two light pulse distributions are both random, therefore coincidence would be rare, and we would be increasing the number of pulses of low energy, thus decreasing the average electron energy measured, but increasing the dosage measured (since now little or none is relatively lost).

(c) For electrons tending to stray out of the crystal sides, the dense lucite has nearly as much probability of scattering them back into the scintillator as scattering them further away, since the angle of incidence at the interface is small. This would not increase the number of pulses, since the same electron continues to produce the light pulse, having lost only a little energy in the lucite, but it would increase the amplitude of the light pulse over what it would be if the lucite were absent, thus reducing the effect of 1(b) above.

It should be noted that lucite on the bottom of the crystal has little effect since backscattering is small for all energies(24).

(d) It is impractical to try to decide, on the theoretical basis which of the effects (a) and (b) or (c) will be of greater importance, if either will. Section IV will show the result of an attempt to investigate this matter experimentally. It appears that in any event, at least 50 percent of the electrons which tried to get out of the sides would succeed, even with lucite "guard rails", so that experimental values below the theoretical should not be viewed with alarm. On the other hand, only the small effect of Section II-D would cause a value greater than the theoretical, so an appreciable excess above the

theoretical value would certainly be indicative of a major defect.

4. Conclusion of Theory.

This concludes the theoretical aspect of the problem in all the details which have been considered of major importance by the authors. The next section deals with the equipment used in the experiment, and the following section will compare the results obtained with the theory evolved in the five divisions of this section.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURE

A. Initial Equipment Configuration.

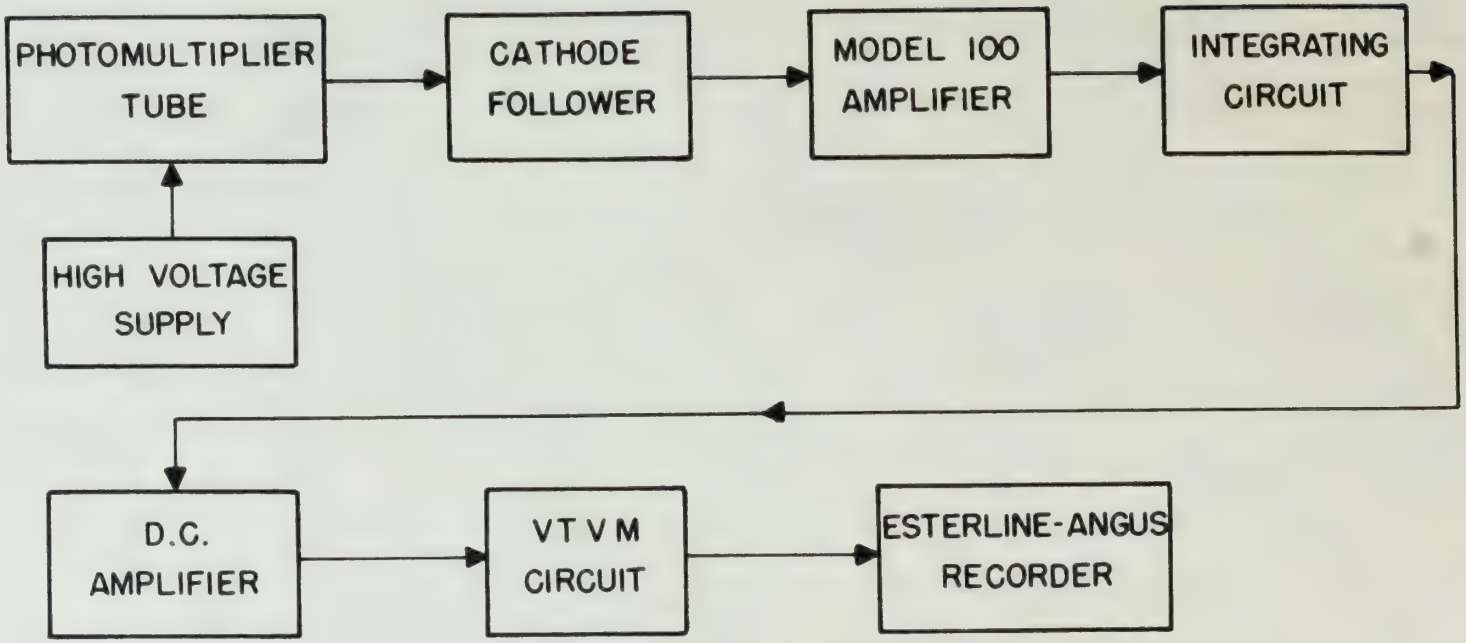
The first approach to presenting the output of the crystal-photomultiplier tube combination in terms suitable for evaluating its relation to dosage was to use the circuits of Figures 3 and 4. All of these components are standard units except the "integrating" circuit (Figure 4). This circuit's principle of operation is mentioned in reference (19), page 250. When it is operated as a counting rate meter, a one-shot multivibrator is placed in front of the "integrator" so that each count appears as a nearly square pulse, constant in amplitude. Under these conditions one can meet the requirements

$$\frac{1}{n} \gg T > 5R_1C_1 \qquad \text{(III-A-1)}$$

$$E \gg V > E_B \qquad \text{(III-A-2)}$$

$$C_2 > C_1 \qquad \text{(III-A-3)}$$

which are necessary for accurate operation of the circuit. In the above equations the nomenclature is defined in Figure 4. Since the detailed operation of this circuit as a counting rate meter is nowhere completely treated, it is felt worth while here to describe its operation in some detail. Referring to Figure 4, suppose a pulse of amplitude E volts appears at the input. In accordance with equation

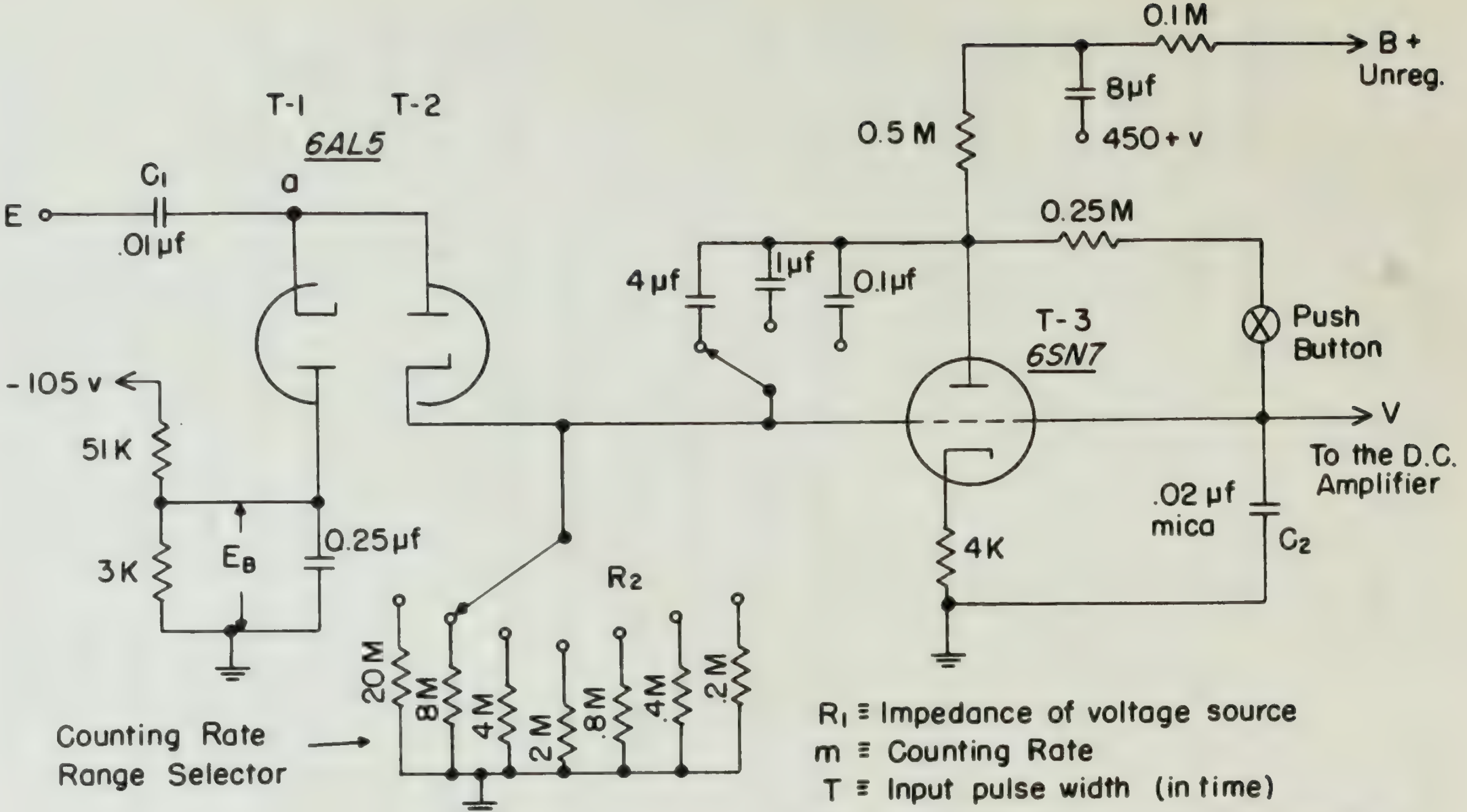


Notes:

(a) PM Tube is an RCA 5819 selected for good resolution.
(b) The Cathode Follower was used to match impedence between PM and Model 100.
(c) Model 100 Amplifier is a standard linear amplifier. See Ref. 19, page 166.
(d) See Figure 4 for circuit diagram of Integrating Circuit.
(e) Esterline-Angus Recorder was a Model AW (Serial No. 32315) 5Ma. D.C. Graphic Ammeter manufactured by the Esterline-Angus Co., Inc. of Indianapolis, Ind.

Figure 3

BLOCK DIAGRAM OF INITIAL EQUIPMENT USED TO "INTEGRATE" OUTPUT FROM PHOTOMULTIPLIER TUBE



R_1 ≡ Impedance of voltage source
m ≡ Counting Rate
T ≡ Input pulse width (in time)
Note: All voltages are specified relative to ground potential

Figure 4

CIRCUIT DIAGRAM OF THE "INTEGRATOR"

(III-A-1), C_1 will be charged to the peak value (E - V). Since $C_2 >> C_1$ an amount of charge proportional to (E - V) (or to E if E >> V) will also be placed on C_2 through T-2 during T. It should be noted that T-3 and its associated circuitry serves only to increase the apparent size of C_2. At the end of the pulse T-2 no longer conducts while T-1 provides a path for the charge on C_1 to discharge to ground, thus returning point a to voltage E_B (some small negative voltage). Thus for each count a constant amount of charge is placed on C_2 which then gradually leaks off through R_2 with time constant R_2C_2 providing a smoothing action on voltage V. Thus V is a stable indication proportional to the counting rate. For further details on counting rate meters and their statistics see references (19) and (20).

In the present problem the application of this circuit, though superficially quite similar to that of the counting rate meter, is somewhat different. To get a measure of energy absorbed by the secondary electrons in the crystal one must sum over all pulse amplitudes, which are proportional to the energy of the electron causing the pulse(7,8) and over the number of pulses. Since, in theory, if the pulses are fed from the photomultiplier (after suitable amplification and clipping) directly to the "integrator" each pulse should deposit a charge on C_2

proportional to $(E - V)$ or E if $E >> V$. Now, since $V = mq_2R_2$ or mC_1ER_2 (19), this voltage, V, should be proportional to the total energy per unit time of the secondary electrons in the crystals. Referring to Section II-E we see that this corresponds to formula (II-B-4), in that $E_T \propto m\mu_a E_\gamma$.

Unhappily, there are factors at work which make this circuit quite unsuitable. Extensive time was devoted to showing experimentally that this was indeed true. It is also easy to show theoretically.

The first difficulty arises in that the spectra of pulses used as input to this circuit range in magnitude from some very small value up to a maximum determined by the energy of the gamma rays of the radioactive source being used and the amplification required. Thus over the lower portion of the spectra E may be comparable with or even less than V. If E is comparable with V the charge going into C_2 is now proportional to $(E - V)$. Thus, the smaller pulses will not be weighted enough according to their true amplitude. If $E < V$ the pulse will not be recorded at all.

The second difficulty arises if there is any overshoot on the input pulse. If the overshoot goes more negative than E_B, then T-1 will conduct, charging C_1 in such a manner that point a will be left positive relative to ground when

T-1 stops conducting after the overshoot voltage becomes less negative than E_B. Thus if the overshoot went negative greater than an amount (E_B + V) an additional charge will be put on C_2, though small in magnitude.

There are, then, two sources of error, one tending to decrease the measured dosage while the other tends to increase it. Both of these errors were observed in this equipment and after very extensive experimentation using both pulse generators and radioactive sources, it was concluded that the circuit could not be operated at a satisfactory level of accuracy for research on this problem.

Since the amount of error introduced by overshoot is very sensitive to E_B it was found that, for a particular spectrum, E_B could be adjusted to give a reasonable value, but if any other source with either a different differential pulse height distribution or maximum pulse height were used error, of course, again was introduced. Furthermore, it was necessary to "know the answer to get the answer" by adjustment of E_B.

It is possible, of course, to remove the overshoot in the pulse and still retain the amplitude; however this solves nothing since the error due to small values of E enters. This error, also, is a function of the differential pulse height distribution of the spectra used.

The conclusion that this "integrating" principle is not sufficiently accurate for research purposes is well borne out by Glass and Hurst at Oak Ridge who after much investigation evolved a very complex circuit([illegible]) which was satisfactory for dosage indications; however, due to its complexity, it was extremely difficult to keep the unit in routine operation.

This discussion is not to be construed as concluding that this instrument cannot be made accurate enough to be used for survey purposes or other more routine dosage measurements. It appears quite probable that one could develop such an instrument, though its relative cost compared to common survey instruments would render its practicability questionable.

B. Final Equipment Configuration.

1. New Approach to the Problem.

Having experienced such difficulty with the equipment described above, it was decided to abandon further attempts in that general line in view of the length of time remaining to the authors at this institution, and to attack the feasibility problem from the standpoint of physics with an entirely different approach. We have seen above that the initial equipment was intended to average the product of

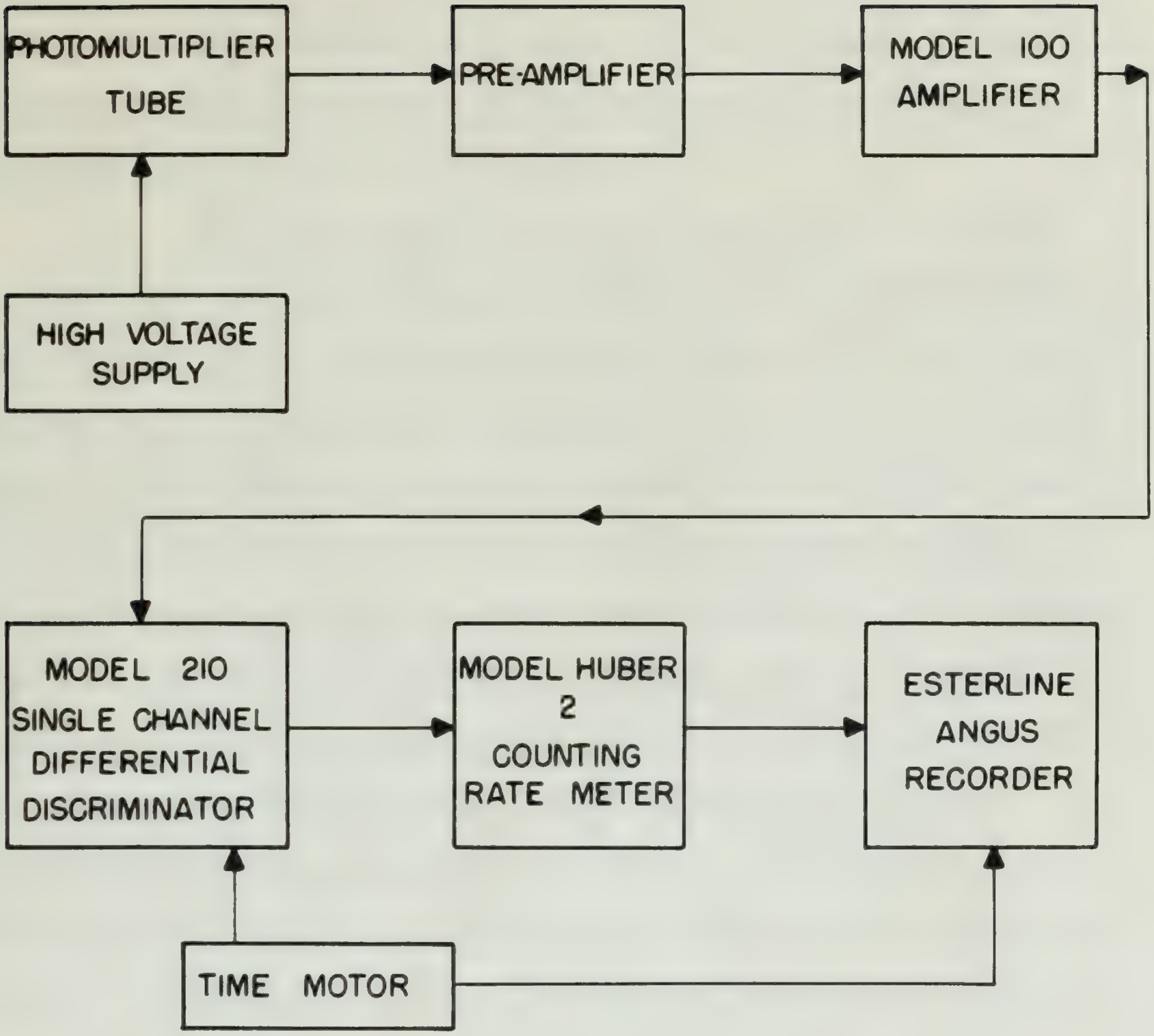
number of electrons produced per unit time and the energy of each. The final equipment decided upon gives readings from which this figure can be calculated; thus, as mentioned in the introduction, the human being has replaced part of the electronics.

2. Description of the New Approach.

The final equipment is shown in block diagram in Figure 5. All of the parts are standard instruments available at this institution. An identical configuration has been and is being used by Dr. G. J. Hine in his gamma ray spectrometer studies with a sodium iodide crystal(21). Let us see what changes were made from the initial configuration and indicate the purpose of each component part:

(a) No change was made in the photomultiplier tube and mount, except for the obtaining of a "good" 5819 tube known to have good resolution, which we will see is required in energy calibration for this method. The high voltage supply was the same one, except that it was replaced late in the experiment by a more stable one, this change producing no effect in the results. All through the data runs on which our results are based, the high voltage supply to the photomultiplier was set at 740 volts.

(b) In order to get a higher gain for the small pulses from the low energy source (Hg^{203}) the preamplifier was changed from a cathode follower to a stage of gain of about 10.



Note: See Section III - B for Description of Operation.

Figure 5

BLOCK DIAGRAM OF FINAL ELECTRONIC EQUIPMENT

(c) The Model 100 amplifier was unchanged, except that it was operated at lower gains for the higher energy sources, so that the output never exceeded 95 volts. Output voltages above 100 volts are unreliable due to the overloading of this type amplifier.

(d) The output from the Model 100 was now led into a Model 210 single channel differential discriminator with window width of about 2 volts. The exact value of window width is of extreme importance and will be discussed later. The Model 210 window position was controlled with a motor-driven rheostat which swept the ranges of 0-96 volts in approximately an hour and 10 minutes. This rheostat and its dial were carefully calibrated using a calibrated voltmeter, pulse generator with variable amplitude signal and Techtronix synchroscope. The calibration curve is included in Appendix B as Figure B-1. It was found that discriminator did not work properly below a value of window center = 2.6 volts, and all data taken were begun at this minimum.

(e) The output from the Model 210 discriminator was then fed into a Model Huber-2 Counting Rate Meter, with internal calibration for scales of 5000 cpm, 10,000 cpm, 20,000 cpm, which were the only scales used. Before each run, the CRM was carefully zeroed and each scale calibrated on 3600 cpm (line 60 cycle AC).

(f) Finally, the CRM output was displayed on an Esterline-Angus 5 ma recorder, with motor feed connected to the motor of the motor-driven dial so that stopping of discriminator rheostat motor also stopped Esterline-Angus tape feed.

3. Mounting of Gamma Sources.

The sources of gamma radiation were supported above the crystal using the usual laboratory stand with an extension arm so that the stand members were at least 40 cm from the vertical line between source and crystal, to minimize the effects of scattering by adjacent equipment. The sources were of various strengths uncalibrated except for the 428 μc Co^{60} and 904 μc of Ra. They were placed at various distances, which were measured to ±0.5 mm, such that convenient CRM scales were available. These distances were recorded, and were reproducible in the main.

4. Phototube Mounting.

A word about the phototube mounting shown in Figure 6 is next necessary. The voltage divider for supplying dynode voltages is contained in the metal box containing the 5819 socket.

The resistors are arranged to give a 40 percent greater voltage rise from cathode to first dynode than from dynode to dynode the rest of the way, other steps being equal. This arrangement provides better collection of

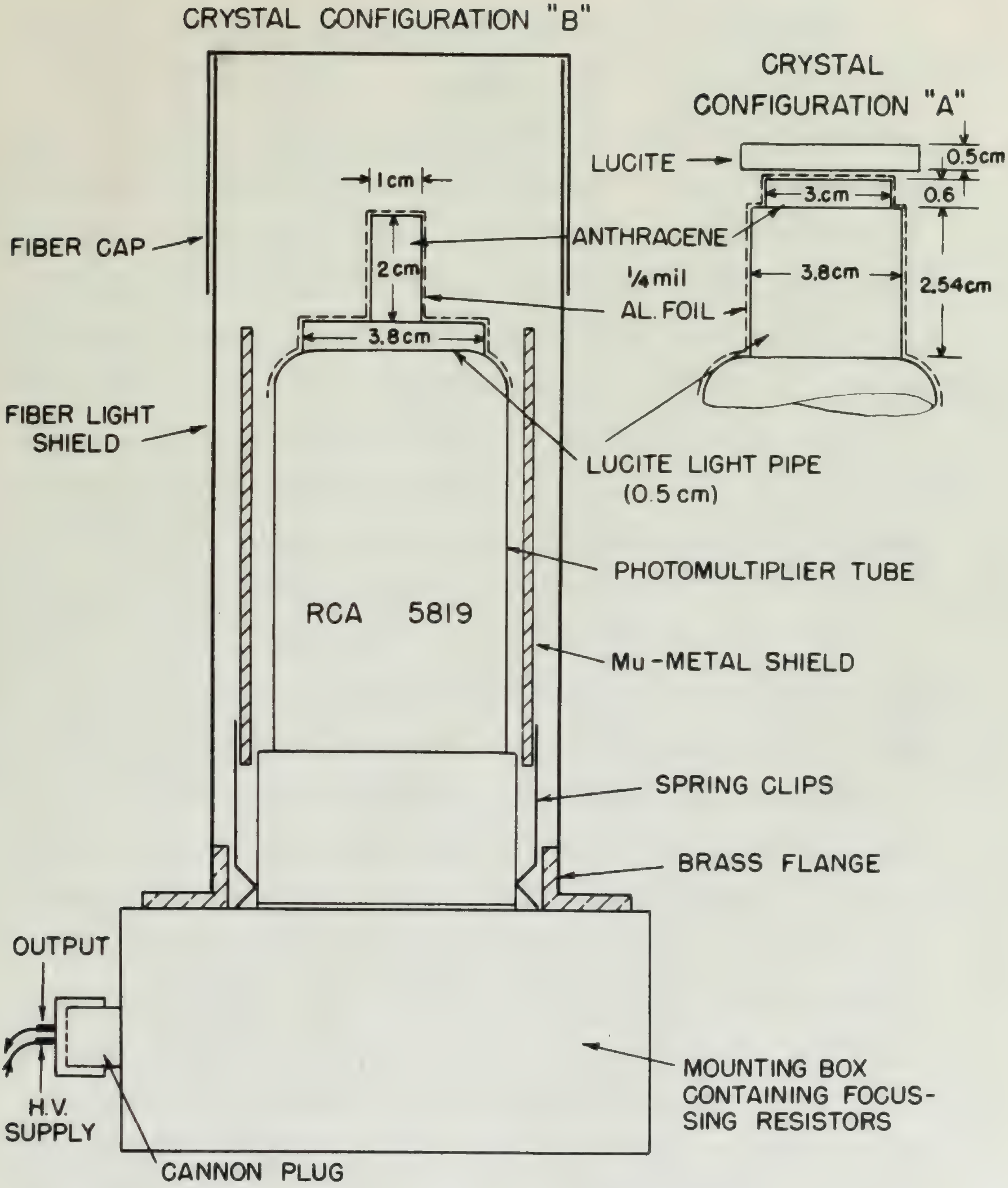


Figure 6

DETAILS OF SCINTILLATION COUNTER CONSTRUCTION

cathode emitted electrons and improves resolution(27). A cardboard light shield is placed over the entire phototube and crystal assembly, and over all, a black cloth is draped. A low background obtainable is considered proof that light-tightness is nearly perfect. Cardboard was used in place of brass to minimize any "scattering-in" of soft gamma rays from the light shield. It was also found that movement of iron apparatus in the vicinity affected the output considerably. A mu-metal shield was therefore installed as shown in Figure 6 and magnetic effects disappeared.

The crystal configurations "A" and "B" as shown in Figure 6 will be discussed later.

5. Data Taken.

We shall outline in brief now what data were obtained and what information can be obtained therefrom. With each source and crystal configuration, a gain on the Model 100 amplifier was chosen such that the largest pulses from the crystal were just below the maximum window height. A minute source (practically weightless point-source) of Cs^{137} was used to calibrate the window center voltage to kilovolts energy at this particular gain and phototube high voltage. This was done by placing the calibration source directly on top center of the anthracene crystal (which was covered with 1/4 mil (1.7 mg/cm^2) aluminum foil) and observing the

position of the window center for the Cs^{137} conversion electron peak (625 Kev line spectrum of e^-). A representative peak is shown in Figure B-2. This method has also been used by other investigators(23). It was determined experimentally that this thickness of aluminum foil caused no error in the energy calibration, since tripling the thickness of the foil caused no detectable shift in the position of the Cs^{137} peak. Then with calibration source removed and sample source in place on its stand, by letting the motor sweep the discriminator rheostat through the range of energies of the particular spectrum, a curve of the number of pulses per energy interval (window width converted into Kev by Cs^{137} calibration being the energy interval and termed herein ΔE) versus their energy at the center of the interval was obtained. That is, a curve of $\frac{dN}{dE}\Delta E$ (cts/min) versus E(Kev) was the directly plottable output of the equipment. Finally, for each spectrum, a run was made sans source to determine background to be subtracted.

Now we see that ΔE, the window width in Kev, is of supreme importance where the absolute number of counts in the entire spectrum is desired, since an increase in E causes an increase in the ordinate ($\frac{dN}{dE}\Delta E$) and when obtaining the integral counting rate by measuring the area under the curve and dividing by ΔE as is further explained in Section

IV, ΔE must be known to the accuracy desired in the integral counting rate. This major difficulty, as will be discussed, is an intrinsic fault of a differential discriminator since it is difficult to measure and even more difficult to keep constant or reset to the same value when it drifts off due to the usual changes in a complicated multivibrator instrument due to tube age, temperature, and line voltage variations. It is the *major* source of error in our experiments regarding dosage, but is of little or no importance in the measurements involving E_{AV}, as shown in Section IV. Changes in ΔE *were* observed to occur *during* several runs, but these were recognizable from experience and such runs were discarded and repeated.

Now that we have seen what the final equipment was, and what quantity it measured, we shall spend Section IV in examining what knowledge can be extracted therefrom and how our results thus obtained compare with the theory evolved in Section II.

IV. EXPERIMENTAL RESULTS AND COMPARISON WITH THEORY

A. General Mathematical Procedure and Preliminary Results.

1. Obtaining E_{AV} and Dosage from Experimental Measurements.

We have seen in the preceding section that the directly plottable output of the final equipment was $\frac{dN}{dE}\Delta E$ vs E, in the previous notation. If now the ordinate of each point on the curve is multiplied by its abscissa, we obtain a curve of $E\frac{dN}{dE}\Delta E$. In order to plot this on the same sheet a scale factor is usually used. All of the spectra shown in Appendix B (Figures B-3 through B-18) are of this type and on each is shown scale factor and window width (ΔE).

Having plotted these curves, one next uses a planimeter and obtains the area under each one. Each curve was planimetered at least 5 times and an average area used in further computations. The accuracy of this operation was better than 1 percent.

Thus we have two areas:

$$\text{(a)} \quad \int_0^{E_{max}} \left(\frac{dN}{dE}\Delta E\right) = \Delta E \int_0^{E_{max}} \left(\frac{dN}{dE}\right) dE$$

[since ΔE = constant for each run (III-B-5)]

$$\int_{0}^{E_{max}} \left(\frac{dN}{dE}\Delta E\right) dE = \Delta E \times N \quad \text{Kev} \times \text{counts/min.}$$

$$\text{(b)} \quad \int_{0}^{E_{max}} \left(E\frac{dN}{dE}\Delta E\right) dE = \Delta E \int_{0}^{E_{max}} \left(E\frac{dN}{dE}\right) dE$$

$$= \Delta E \times E_T \quad \frac{\text{Kev} \times \text{Kev}}{\text{minute}}$$

That is, (a) is the total number of counts/minute in the spectrum multiplied by the window width in Kev; and (b) is the total energy absorption by secondary electrons *measured* in the crystal multiplied by the window width in Kev. If now we divide (b) by (a) we obtain the average secondary electron energy, and notice that is is independent of ΔE:

$$E_{AV} = \frac{\Delta E \times E_T}{\Delta E \times N} = \frac{E_T}{N}$$

However, if we are interested in the dosage, which is in turn related to the total energy absorbed by the secondary electrons, we find that we must know ΔE accurately.

It should be noted that the integration carried out was from *zero* to E_{max}. Since this required a somewhat arbitrary extrapolation of each curve to zero, the area under the extrapolated curves *and* the area under the

unextrapolated curves was measured. The figures for both are plotted in Figures 7 and 8 and it is seen from Figure 8 that the extrapolation gives a point which is lower by a constant percentage. Thus, for ease in comparison, only the unextrapolated curve areas are considered hereafter, in that they involve no arbitrary extrapolation assumptions.

Returning now to (b), and assuming we know ΔE in Kev exactly, we see that we have measured the total energy of the secondary electrons per minute; i.e., the rate of energy absorption of the whole crystal from the gamma beam. How then can we convert this to "dosage"? To begin with, it is necessary to know the mass of crystal in which the absorption occurred. The crystals are therefore weighed:

Thin (6 mm crystal) = 5.023 gms.
Thick (20 mm crystal) = 6.098 gms.

Thus we obtain the energy absorption rate in terms of Mev/min-gm anthracene. But the roentgen can be expressed as 5.24×10^7 Mev/gm-air. Since we expect from Figure 1 that Compton effect predominates in the range considered, the only difference between air and anthracene lies in the number of scattering centers per gram; that is, the number of electrons per gram, which was computed in Appendix A:

$n = 3.007 \times 10^{23}$ electrons/gm air

$n = 3.18 \times 10^{23}$ electrons/gm anthracene.

Thus by multiplying our energy absorption rate in Mev/min-gm anthracene by $\frac{3.007}{3.18}$ and dividing by $\frac{5.24 \times 10^{7} \text{ Mev}}{\text{gm air}}$, we can obtain dosage rate in roentgens per minute; or more conveniently by a time correction, in milliroentgens per hour.

It must be remembered that we assumed that ΔE was known exactly. This assumption is not experimentally valid as has been mentioned in Section III-B; the result of its variation from run to run will be shown later in this section.

The possible correction for crystal thickness mentioned in Section II-C has not been made at this point. Refer to Section IV-C for the experimental merit thereof.

It should finally be noted that the decay of Na^{24} ($T_{1/2}$ = 15 hrs) during the 1 hour runs was accounted for by correcting the observed counting rates prior to plotting.

2. Preliminary Results and Selection of Crystal Configurations.

Before proceeding with measurements with all sources, it was desired first to see the gross effects of crystal configuration change with different conditions, such as length of light pipe, thickness of crystal, lucite plate on top of crystal and type of reflector. Many runs were

made with the cobalt and mercury sources under many configuration changes, and evaluation of them was made by comparison of spectral shapes. We will not bore the reader with enumeration of all these runs. The important effects noted are shown in Figures 9 and 10. In general, it was discovered that:

(a) Some light pipe was advantageous in that the light was distributed more evenly over the photo cathode, though length of light pipe was not an important factor. The light pipe also facilitated fitting the crystals to the curved top of the photomultiplier tube.

(b) A 1/4 mil (0.00025 in) aluminum foil reflector in smooth contact with all top and side crystal faces was very satisfactory.

(c) Figures 9 and 10 show that the spectral shape from cobalt was little affected by crystal thickness, while the mercury spectrum was more peaked for the thin crystal. In order to be sure that the geometry, and not the different crystal, was responsible for this difference, a run was made with the thick crystal on its side, with the 10 mm dimension vertically oriented. As Figure 10 clearly shows, the geometry was the cause of spectral shape change.

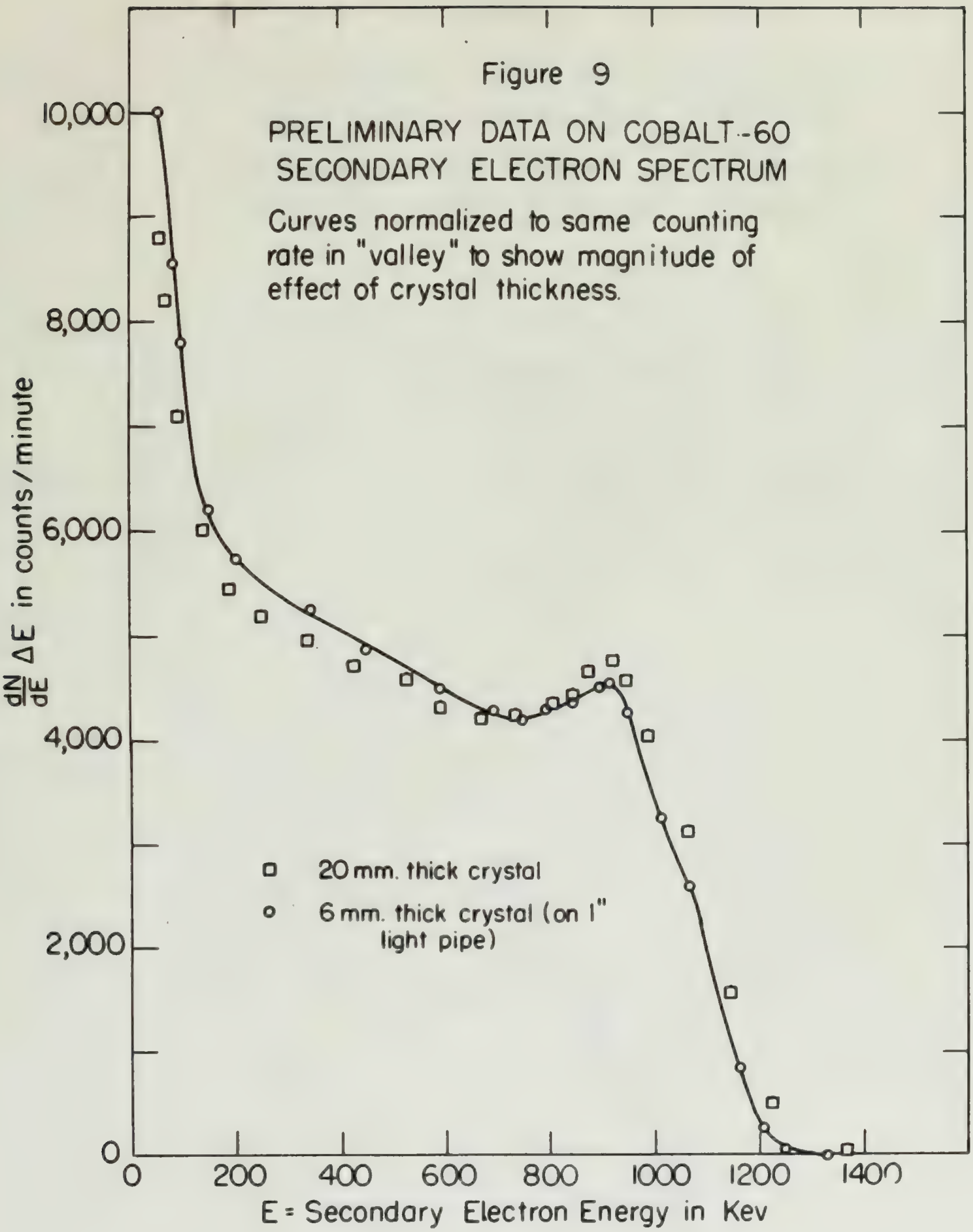


Figure 9

PRELIMINARY DATA ON COBALT-60 SECONDARY ELECTRON SPECTRUM

Curves normalized to same counting rate in "valley" to show magnitude of effect of crystal thickness.

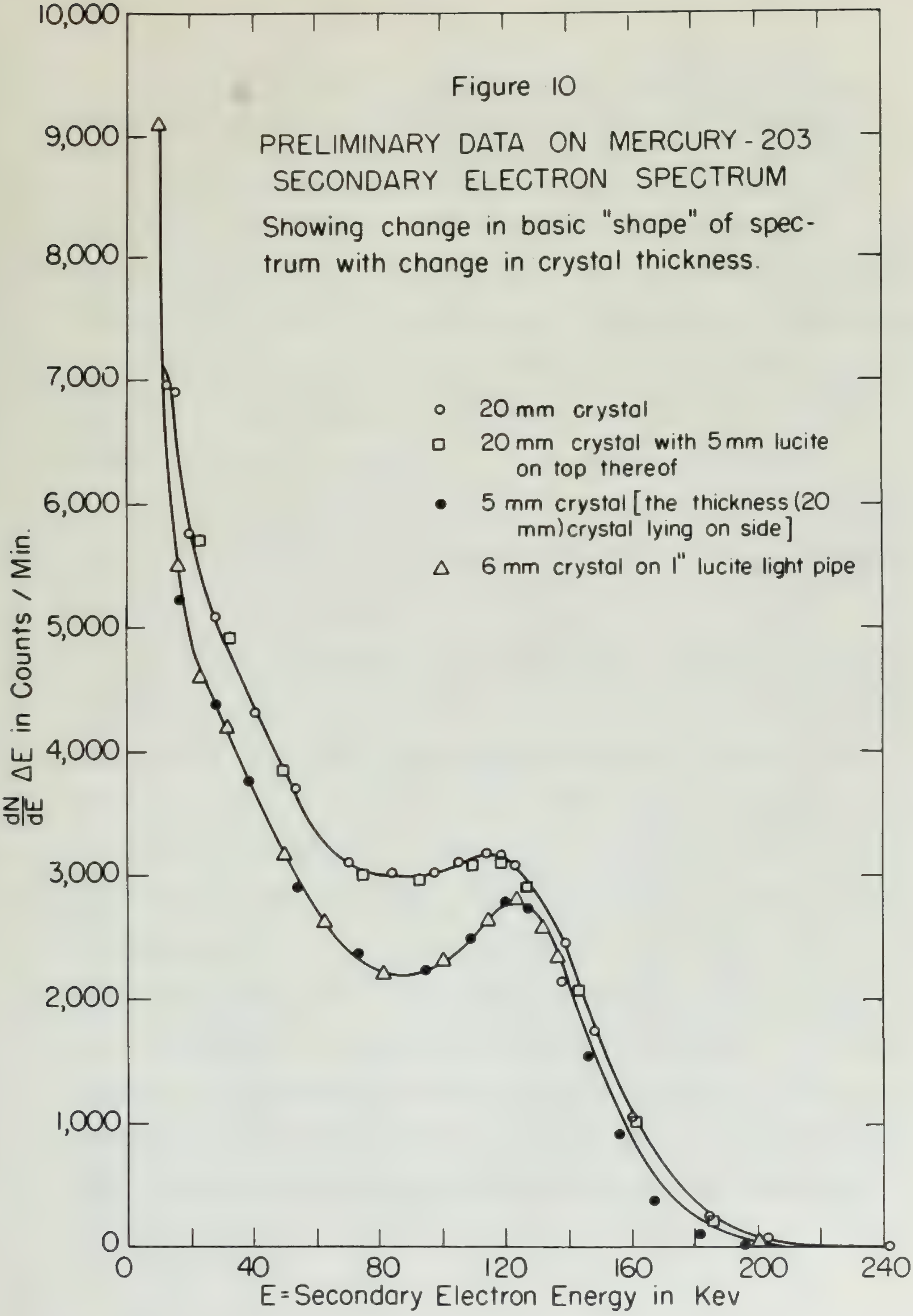


Figure 10

PRELIMINARY DATA ON MERCURY - 203 SECONDARY ELECTRON SPECTRUM

Showing change in basic "shape" of spectrum with change in crystal thickness.

(d) Finally we see that the lucite plate atop the thick crystal made no difference to either spectrum.

Therefore, in order to obtain results chiefly dependent upon crystal thickness, the obviously most important variable, configurations "A" and "B" were chosen (Figure 6), with "A" involving the 6 mm crystal, "B" involving the 20 mm crystal. As a last determination, occasioned by the results with "A" and "B", another run was made with sodium using "B" enclosed in a 13 mm thick lucite box. This configuration is not shown; the results are described below. The results of all runs on "A" and "B" are included in Figures B-3 through B-12.

A point of general interest, before proceeding with specific results, is the general shape of all spectra. One should note that the large number of small pulses is not due to background or noise since each curve has been corrected therefor. The tailing off at high energies is due to phototube resolution and the statistical variation of emission from the photo cathode, as is borne out by the shape of the Cs^{137} conversion electron "line", Figure B-2. The curves showing the greatest difference in spectra between configurations "A" and "B" are those for sodium, where we see that the thicker crystal gave a much higher $E\frac{dN}{dE}\Delta E$ value at the high end of the spectrum. Finally,

the peak is termed a "Compton Peak" and corresponds to the most probable energy obtained in Compton collisions; qualitatively, it appears where it should be, somewhat below the maximum energy of Compton electrons as computed by formula (II-E-1).

B. Average Secondary Electron Energy Results and Theory Correlation.

1. Presentation of Results.

The tabulation of Table II-C-1 is repeated here, with experimental values added. These data are also displayed in Figures 7 and 8, in which the logarithmic plot is included to show the *relative* deviation of the points from the theoretical curve.

TABLE IV-B-1

Source	$\bar{E}_\gamma$	Crystal Conf.	E_{AV} (exper)	E_{AV} (theoretical) Partially Corr.	Totally Corr.
Hg^{203}	280 Kev	A	68.8 Kev	72.1 Kev	72.1 Kev
Cs^{134}	698 Kev	A	250 Kev	271.5 Kev	265.9 Kev
Co^{60}	1.25 Mev	A	506 Kev	586. Kev	584. Kev
Na^{24}	2.07 Mev	A	800 Kev	1.109 Mev	1.028 Mev
Ra	~1.06 Mev	A	422 Kev	-	-
Hg^{203}	280 Kev	B	71.6 Kev	72.1 Kev	72.1 Kev
Cs^{134}	698 Kev	B	258 Kev	271.5 Kev	268.5 Kev
Co^{60}	1.25 Mev	B	555 Kev	586. Kev	584. Kev
Na^{24}	2.07 Mev	B	841 Kev	1.109 Mev	1.037 Mev
Ra	~1.06 Mev	B	456 Kev	-	-

The experimental values tabulated are from the unextrapolated curves as was mentioned in IV-A-1. In addition to the data plotted above, another Na^{24} source was obtained, which happened to be stronger than the source for which values are tabulated in Table IV-B-1, and had to be placed at three times the previous distance used for sodium. This source was run on configuration "B" and on "B-1", the latter being "B" encased in a lucite box (13 mm thick) on sides and top, seeking the effect mentioned in II-E-3(c). The spectral curves for these runs are not included since they appear nearly the same as Figures B-9 and B-10. The values of E_{AV} and dosage obtained from them, however, differ appreciably. Data obtained:

Configuration	E_{AV}
"B"	908 Kev
"B-1"	971 Kev

The increase in E_{AV} for "B" over that shown in Table IV-B-1 is attributable to the change in distance, since by Section II-E, the leakage would be less with a more parallel gamma beam; i.e., for the greater distance. The maximum divergence of the beam from the vertical was 2.9° for the shorter distance and only 0.95° for the longer distance. Accordingly, for comparing the effect of the lucite box (B-1) to the earlier sodium data

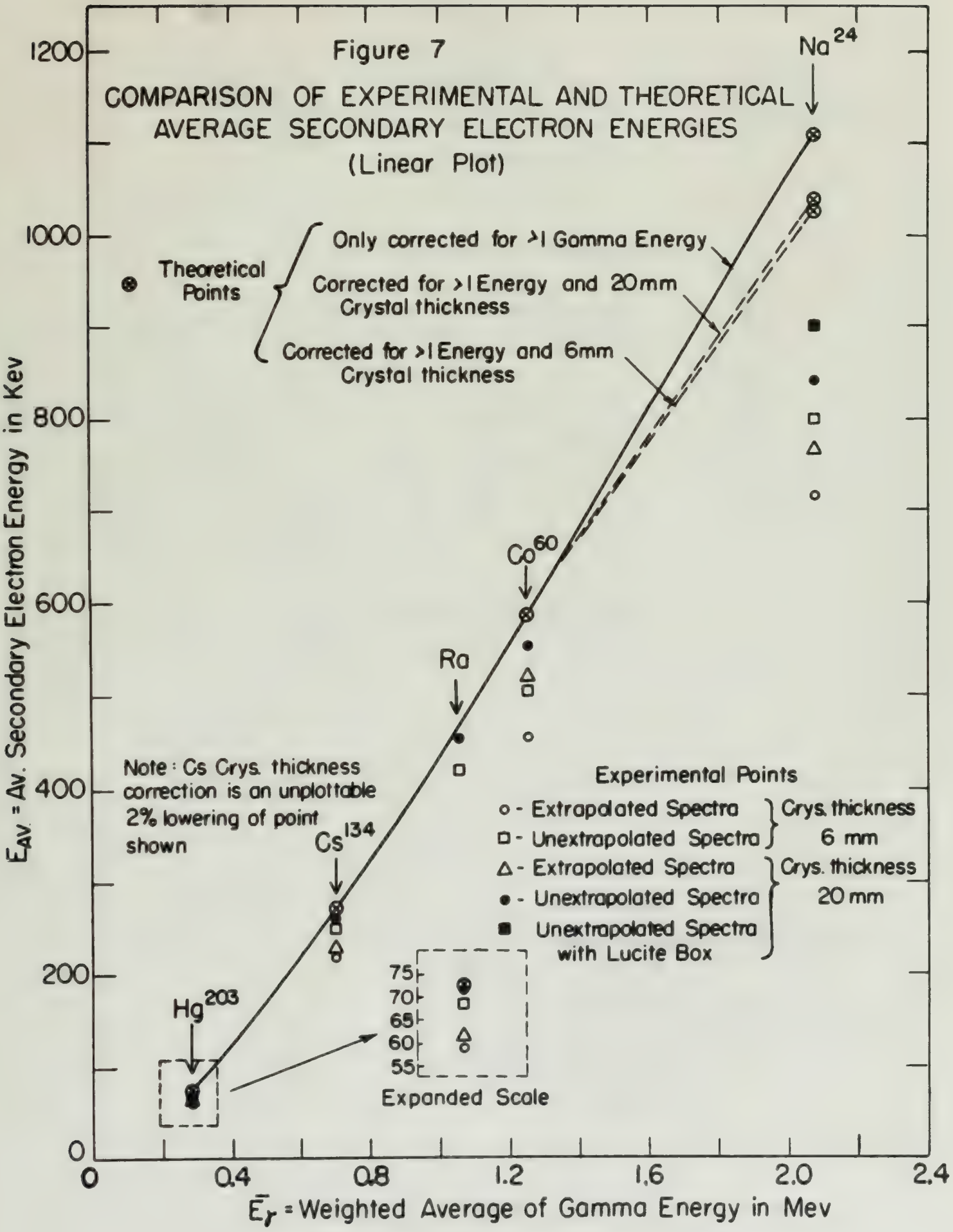


Figure 7

COMPARISON OF EXPERIMENTAL AND THEORETICAL AVERAGE SECONDARY ELECTRON ENERGIES (Linear Plot)

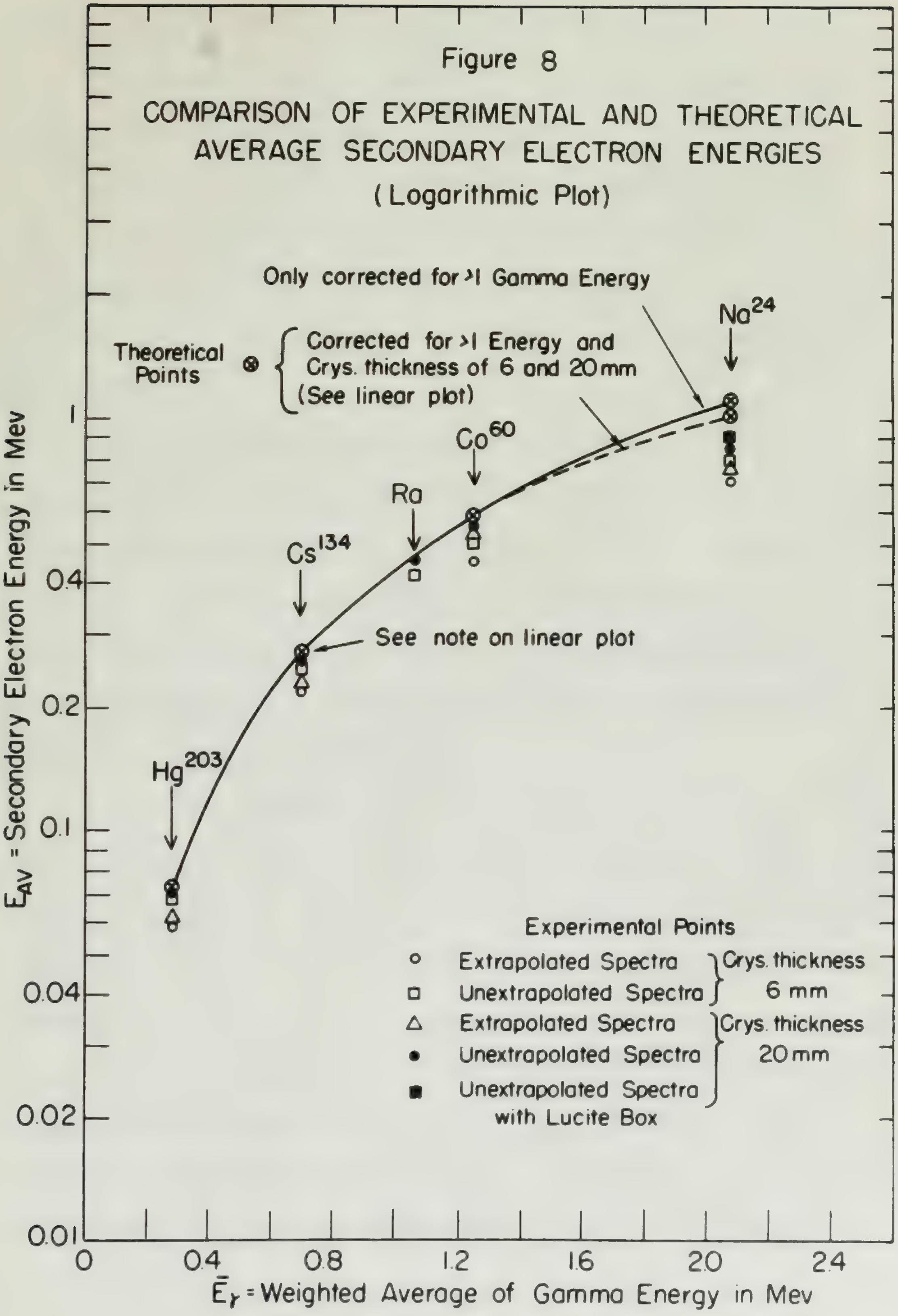


Figure 8

COMPARISON OF EXPERIMENTAL AND THEORETICAL AVERAGE SECONDARY ELECTRON ENERGIES

(Logarithmic Plot)

(which are plotted in Figures 7 and 8), E_{AV} for "B-1" was corrected to that distance with a linear approximation and plotted as $971 \times \frac{841}{908} = 900$ Kev.

The values of $\overline{E}_{\gamma}$ for Ra are obtained by fitting the E_{AV} points obtained to the curve connecting the corresponding points for the other sources. Comment on the value of $\overline{E}_{\gamma}$ obtained for Ra will be reserved for Section V.

8. Interpretation and Evaluation.

A number of very interesting results are obtainable from a close inspection of Figures 7 and 8. Figure 8 is probably of more value, since its logarithmic ordinate scale presents constant ratios or percent difference as constant distances. These points are enumerated for clarity and easy reference:

(a) _First_, we note that _all_ measured E_{AV} are _below_ the theoretical values. This is in agreement with Section II-E-3(d) page 38, and substantiates the belief that plural scattering was of little importance in our crystals.

(b) _Secondly_, all of the values for the thick crystal are _above_ those for the thin crystal. This is as predicted in II-E-2, page 36. Of course, this conclusion is the result of one measurement on each configuration

for each of 5 sources, and there is a finite chance that this could be a coincidence. However, if we considered that there *should* be equal values for thick and thin crystal and that probability and randomness were the cause of one being higher than the other, then the chance of *all* of the thick crystal values being greater than the thin crystal values is, of course, $(\frac{1}{2})^5 = \frac{1}{32}$. True, we may have had the one chance in 32 occurring; only further experimentation by other parties will tell. However, the authors feel strongly that this is a physical phenomenon explainable by Section II-E-2.

(c) Next we see that the "totally corrected" curve is closest to the experimental results; and that for low energies, the experimental points are very close to the theoretical, differing from it by a nearly constant ratio for energies less than 1 Mev, with a *slight* increase in error at Co^{60}, and a considerable increase in error for the energetic gammas of Na^{24}, as also manifested by the spectral shape, as noted in Section IV-A-2 (page 58). The trend away from the theoretical curve at high energies is in conformity again with Section II-E; and further substantiation to the argument regarding electron leakage and its correction, per Section II-E-3, is the rise of the sodium point with configuration B-1. This indicates that

the effect of "scattering-in" of II-B-3(c) predominates over the "compensating" effect of (a) and (b), same section.

Thus, the majority of our theory is confirmed. In general, the anthracene crystal is "air-equivalent", but crystal geometry must be considered in designing a scintillation dosimeter for gamma energies above 1.25 Mev, since the effects of secondary electron leakage become increasingly important with increasing energy, and these effects are apparently the ones which cause a deviation from true air equivalence. Round crystals of about 20 mm diameter and 20 mm in thickness, surrounded with a lucite cylinder of wall thickness of $\sim$10 mm would appear to be the best geometry, and experimentation therewith is recommended.

C. Attempt at Dosage Evaluation.

1. Procedure.

In order to evaluate the dosages as obtained from the integration of the curves as described in Section IV-A-1, a Keleket dosimeter was obtained. The calibration curves for this chamber are included in Appendix B as Figures B-13 and B-14. The dosimeter was placed in the crystal's position and runs made on all sources for a number of

hours necessary to obtain a reasonable reading on the scale of 200 mr. The dosimeter run on Na^{24} with its short half-life was corrected back to the zero time of the discriminator run by the easily derivable formula:

$$R_o = \frac{D\lambda}{(e^{-\lambda t_1} - e^{-\lambda t_2})} ;$$

in which D = total (less background) dosage measurement, λ = decay constant, t_1 = time of beginning dosimeter exposure, t_2 = time of ending exposure, R_o = dose rate at zero time (beginning of discriminator run). A similar formula was used to convert the reading on 46.5 day Hg^{203} back an interval of some 10 days to the day of its discriminator run.

The dosage exposure runs required a good deal of exposure time, as is seen from the dose rates below. For this reason, it was not possible to take enough exposures to get a low statistical standard deviation, as may be seen by Table IV-C-1, and, as will be shown, the variation of window width made further attempts impractical.

2. Comparison of Computed Dosage and Measured (Dosimeter) Dosage.

As has been mentioned before, the window width ΔE (in volts) varied from run to run in spite of careful

setting of zero sets on the differential discriminator. It should be noted that ΔE in Kev is also a function of the position of the Cs^{137} peak, and is therefore subject to a small error due to the statistical variations therein. In computing the data set forth in Table IV-C-1 by the method of Section IV-A-1, E in Kev was computed using a window width of 1.8 ± 0.1 volts, a conservative estimate of the error. From Table IV-C-1, it can be seen that only qualitative conclusions can be drawn: The computed dosage rate generally agrees with the measured rate within 10 percent. In general, it may be said that this electronic difficulty eliminates the possibility of using this equipment to measure dose rate, though the value of the equipment in establishing the air-equivalence of anthracene is not affected by the difficulty and the results of IV-B above are perfectly valid.

TABLE IV-C-1

Source	Crystal Conf.	Dosage× ΔE (mr/hr×Kev)	ΔE(Kev)	Calc. Dosage (mr/hr)	Observed (Dosimeter) Dosage (mr/hr)
Hg^{203}	A	5.45	5.72±0.3	0.353±0.050	0.944±0.2
Hg^{203}	B	5.56	7.24±0.4	0.770±0.043	0.944±0.2
Cs^{134}	A	49.1	15.5 ±0.8	3.18 ±0.16	3.24 ±0.7
Cs^{134}	B	58.7	18.6 ±1.0	3.16 ±0.18	3.24 ±0.7
Co^{60}	A	633	36.6 ±2.0	17.3 ±0.9	14.7 ±0.3
Co^{60}	B	428	33.0 ±1.8	12.93 ±0.7	14.7 ±0.3
Na^{24}	B	1880	72.8 ±4.0	25.8 ±1.4	31.5 ±2.2
Na^{24}	B-1	2080	73.6 ±4.0	28.3 ±1.5	31.5 ±2.2
Ra	A	384	43.1 ±2.4	8.9 ±0.5	9.19 ±1.3
Ra	B	517	54.3 ±2.9	9.5 ±0.5	9.19 ±1.3

Because of this wide scatter of comparative results, no attempt has been made to include an evaluation of the correction factors of II-C-3(b). Before such could be done, a method of accurate window width determination would be required (see Section V).

The reader is now referred to the following section for a summary of findings and additional interpretation and discussion thereof.

V. SUMMARY AND RECOMMENDATIONS

A. General Conclusions.

From the experimental results as given in detail in Section IV it can be concluded that:

1. Anthracene is essentially air-equivalent in the energy range considered, except as noted in (2) and (3) below.

2. Deviations from air-equivalence will be experienced at higher gamma energies if the scintillating medium is not large enough to eliminate electron leakage; or at the lower gamma energies if the crystal is so large that plural scattering becomes appreciable.

3. Electron leakage can be minimized by surrounding the crystal with a "reflecting" material similar in composition to the anthracene.

4. Dosage measurements made with the scintillation counter were consistent with those made by an ionization chamber, subject to the inaccuracy imposed by indeterminacy in differential discriminator window width.

5. It appears to be very difficult to construct an electronic circuit to display the scintillator output directly in terms of dosage. A circuit was used which gave this indication indirectly.

6. As described in Section IV-B-1, a value of 1.06 Mev for the weighted average energy $(\overline{E}_\gamma)$ of the gamma rays from a radium source with 0.5 mm platinum filtration was obtained. This is consistent with the results of Hine$^{(24)}$, who obtained 1.04 Mev, but somewhat higher than a computed value of 0.84 Mev using the spectrum given by Ellis and Aston$^{(25)}$ and using data from Davisson$^{(9)}$ to compute the effect of Pt filtration. Other spectra mentioned in the literature would give values agreeing more closely with the results obtained herein, but since the value of the weighted average gamma ray energy of a spectrum as complex as radium is in doubt, nothing further can properly be concluded here.

B. Recommendations for Future Investigations.

Since crystal size at higher energies is important further work should be done in getting more detailed quantitative information on the effect. These data will be important to workers using the scintillation counter at energies above ~1.5 Mev.

In order to make the system using the differential discriminator give indication of dosage accurate enough for research purposes, a method of determining the exact window width must be devised. Two such methods are suggested:

(a) Use of a scaler-timer circuit in conjunction with the equipment used by the authors; with discrimination level of scaler matched to the lower level of the differential discriminator. In this way, ΔE can be determined by comparison with the measurement of $\Delta E \times N$ (Section IV-A).

(b) Use of a vacuum tube voltmeter with recording equipment, to monitor ΔE in volts directly across the particular resistor in the differential discriminator which provides the voltage difference ΔE. After this has been accomplished more work can be done on comparing the dosage given by the scintillation counter with that given by the air ionization chamber.

In order to utilize the scintillation detector as a practical instrument for indicating dosage a simple electronic circuit must be designed to sum the photomultiplier output over the number of pulses and pulse heights. One approach is to rectify the output taken directly from the photomultiplier tube to avoid overshoot difficulties. Ter-Pogossian(1) and the Sloan-Kettering Institute(26) have developed two such circuits but no information has been published concerning their accuracy, or other characteristics.

In conclusion, the authors wish to express their sincere thanks to Dr. Robley D. Evans for his invaluable counsel, advice, and encouragement throughout the whole of

this work; to Dr. Gerald J. Hine for his original suggestion of the problem, infinite patience and day-by-day guidance without which little success would have been possible; to Mr. Norman Rudnick for his aid in developing a reasonable theory; to all the personnel of the Radioactivity Center, M.I.T. for their cooperation at all times: Mr. Joel B. Bulkley and Mr. Sidney G. Millen; and finally to Mrs. Grace Rowe for her competent draftsmanship in reproducing the figures included.

APPENDIX A

COMPUTATION METHODS FOR σ, σ_s, τ, K

APPENDIX A

COMPUTATIONS FOR ATTENUATION AND ABSORPTION COEFFICIENTS

1. For air, the required information is available from Goodman$^{(11)}$ and its accuracy in σ and σ_a was checked by recomputing σ and σ_a from ${}_e\sigma$ and ${}_e\sigma_a$ as given in reference (12). In these computations, the percentage by weight of air was used as follows:

Nitrogen	75.8 percent
Oxygen	23.22 percent
CO_2	0.05 percent
Rare gases	0.93 percent

This gave a figure of 3.007×10^{23} electrons per gram, in agreement with Lea$^{(13)}$, which when combined with ${}_e\sigma$ and ${}_e\sigma_a$ and density in gms/cm^2 gives σ and σ_a in cm^{-1}.

2. For anthracene and sodium iodide no ready-made curves were available and each coefficient had to be calculated by the use of appropriate formulas, taking the weight percentage of each element into account.

Anthracene ($C_{14}H_{10}$)

Percent hydrogen by weight = 5.61

Percent carbon by weight = 94.39

Electrons per gram calculation: N = Avogadro's number

$$H:\quad 0.0561 \text{ gms} \times \frac{1 \text{ mole}}{1 \text{ gm}} \times \frac{6.02 \times 10^{23} \text{ atoms}}{\text{mole}} \times \frac{1 \text{ electron}}{\text{atom}} = 0.0561N$$

$$C:\quad 0.9439 \times \frac{1 \text{ mole}}{12 \text{ gms}} \times \frac{6.02 \times 10^{23} \text{ atoms}}{\text{mole}} \times \frac{6 \text{ electrons}}{\text{atom}} = \frac{0.472N}{0.5281N}$$

Therefore electrons/gm = 3.18×10^{23}

ρ = density of anthracene = 1.25 gms/cc.

Sodium iodide

Percent Na by weight = 15.3

Percent I by weight = 84.7

Similar computation to anthracene gives 2.572 elect/gm.

ρ = density of sodium iodide crystal = 3.667 gm/cc.

Thus for these two crystals, knowing the electrons/gm and ρ, we obtain ${}_e\sigma$ and ${}_e\sigma_a$ from reference (12), and compute σ and σ_a as a function of E_γ.

The computation of τ and κ is a bit more difficult. First let us consider the photoelectric effect. Lea$^{(13)}$ gives an empirical photoelectric relation:

$$\tau/\rho = 0.0089 \frac{Z^{4.1}}{A} \lambda^n$$

where λ is the gamma wavelength in angstroms; and tabulates

values of n and of the coefficient of λ^n for various elements:

Element	Coefficient	n
H	0.009	3.05
C	1.150	3.05
Na	7.200	2.85

Therefore for anthracene, weighting each coefficient by the percent abundance of the element, we obtain

$$(\tau/\rho)_{anth} = \Big[(0.0561)(0.009) + (0.9439)(1.15)\Big]\, \lambda^{3.05}$$

$$= \frac{2.067 \times 10^{-6}}{E_\gamma^{\,3.05}}\ \text{cm}^{-1} \qquad (\underline{E_\gamma}\ \underline{\text{in}}\ \underline{\text{Mev}})$$

This weighting method was applied as a check to a determination of τ/ρ for air and the value obtained was in agreement with published values of τ for air(11).

We notice that the value of n in λ^n is not given for iodine, and it was therefore not possible to use the above method completely for sodium iodide.

$$(\tau/\rho)_{Na} \text{ by Lea formula} = \frac{2.644}{E_\gamma^{\,2.85}} \times 10^{-5}\ \ \frac{\text{cm}^2}{\text{gram}}$$

From Victoreen(14) we find

$$(\tau/\rho)_I = 1140\, \lambda^3 - 1163\, \lambda^4 \qquad \lambda \text{ in angstroms.}$$

$$= \frac{2.17 \times 10^{-3}}{E_\gamma^{\,3}} - \frac{2.73 \times 10^{-5}}{E_\gamma^{\,4}}\ \ \frac{\text{cm}^2}{\text{gram}}$$

Then by the usual weighting,

$$(\tau/\rho)_{NaI} = (0.153)(\tau/\rho)_{Na} + (0.847)(\tau/\rho)_{I}$$

from which formula τ_{NaI} was computed.

Finally, κ was computed for both crystals by use of a lead standard curve. Lead was chosen because its theoretical pair production curve has been well checked by experimentation. A Project Rand report$^{(15)}$ tabulates the atomic pair production coefficient σ_{pp} for lead where $\kappa = \frac{N}{A}\rho\,\sigma_{pp}$, N being Avogadro's number, ρ the density, and A the mass number.

Then from Hine$^{(16)}$

$$\kappa/\rho \propto N \sum_{i} p_i \frac{Z_i^2}{A_i}$$

where p_i = percent, by weight, of constituents.

$$\text{Therefore } \frac{(\kappa/\rho)_{lead}}{(\kappa/\rho)_x} = \frac{\dfrac{Z_{lead}^2}{A_{lead}}}{\left(\displaystyle\sum_{i} p_i \frac{Z_i^2}{A_i}\right)_x}$$

$$\text{whence } \kappa_x = \rho_x \frac{\kappa_{lead}}{\rho_{lead}} \; \frac{A_{lead}}{Z_{lead}^2} \left[\sum_{i} p_i \frac{Z_i^2}{A_i}\right]_x$$

Substituting from above, to obtain κ_x in terms of Rand values:

$$K_x = \rho_x N \sigma_{pp} \frac{\left[\sum_i p_i \frac{Z_i^2}{A_i}\right]_x}{Z_{lead}^2}$$

For anthracene the constants evaluate to give

$$(K)_{anth} = 3.22 \times 10^{-3} \sigma_{pp} \text{ cm}^{-1}$$

For sodium iodide, we obtain

$$(K)_{NaI} = 8.27 \times 10^{-3} \sigma_{pp} \text{ cm}^{-1}$$

From these computations, the values of μ and μ_a were calculated for use in Section II. The variation of μ with E_γ is shown in Figure A-1, for anthracene and sodium iodide.

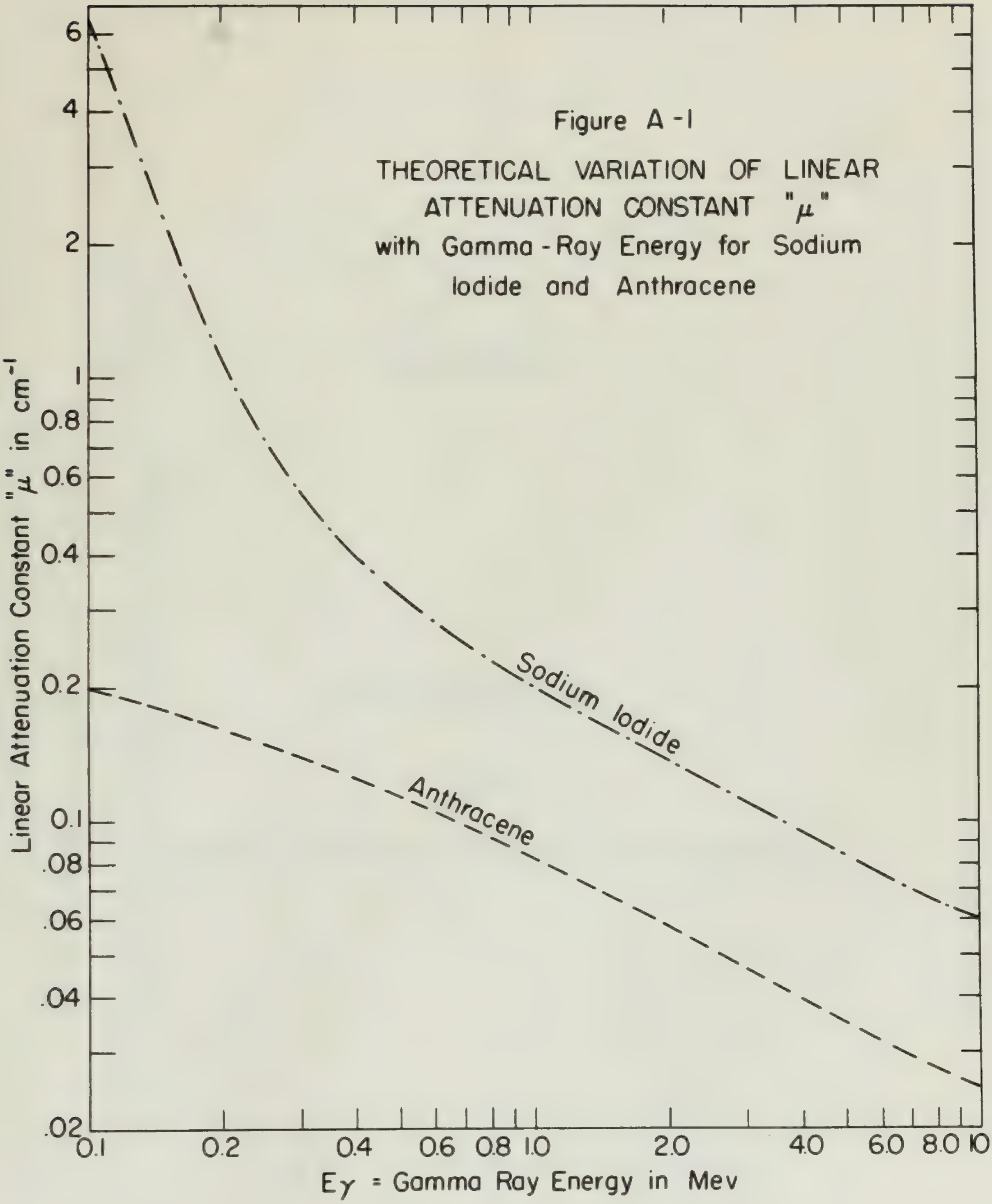


Figure A -1

THEORETICAL VARIATION OF LINEAR ATTENUATION CONSTANT "μ" with Gamma - Ray Energy for Sodium Iodide and Anthracene

APPENDIX B

CALIBRATION CURVES

AND

SECONDARY ELECTRON SPECTRAL DISTRIBUTIONS

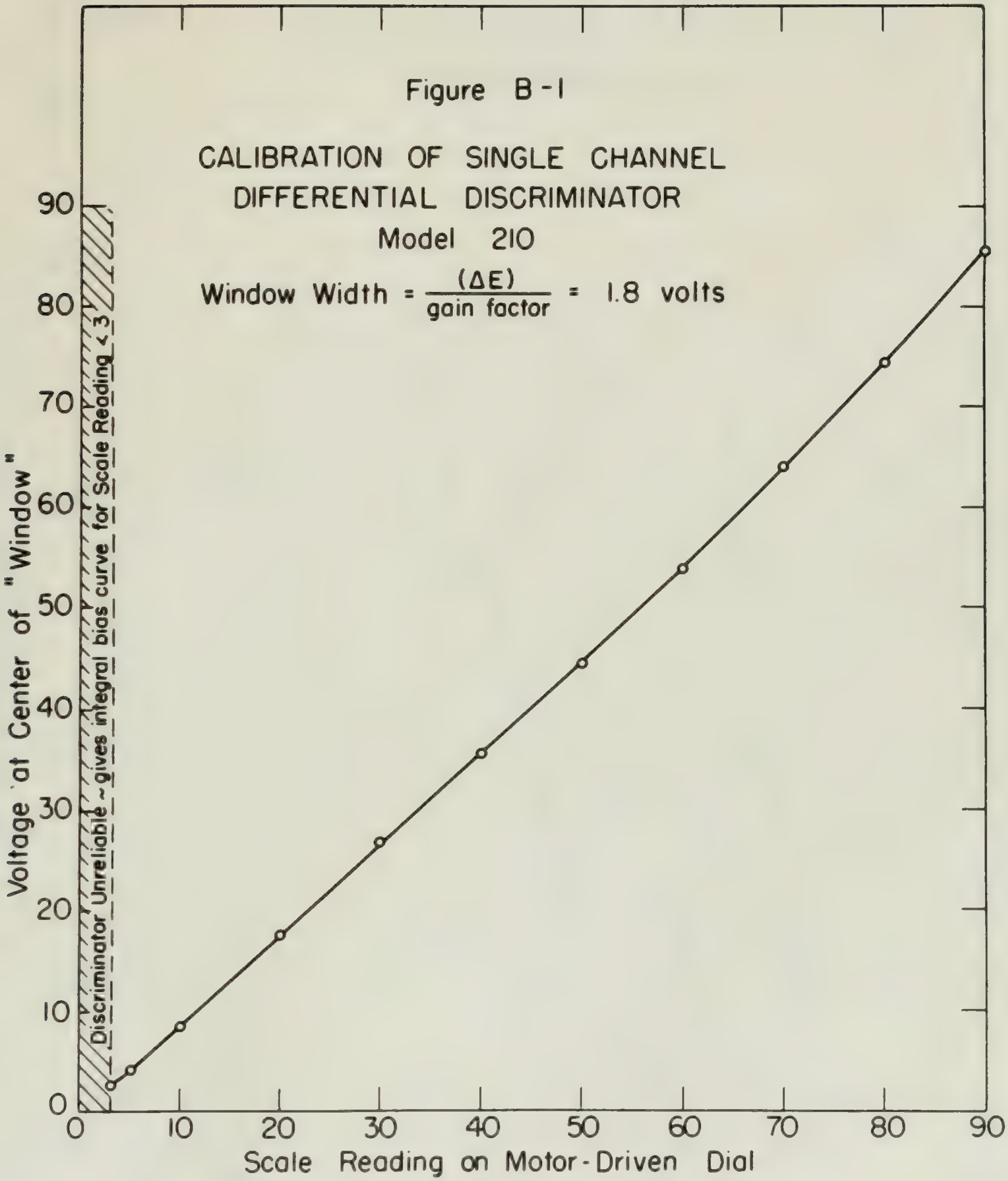


Figure B-1

CALIBRATION OF SINGLE CHANNEL DIFFERENTIAL DISCRIMINATOR

Model 210

Window Width = $\frac{(\Delta E)}{\text{gain factor}}$ = 1.8 volts

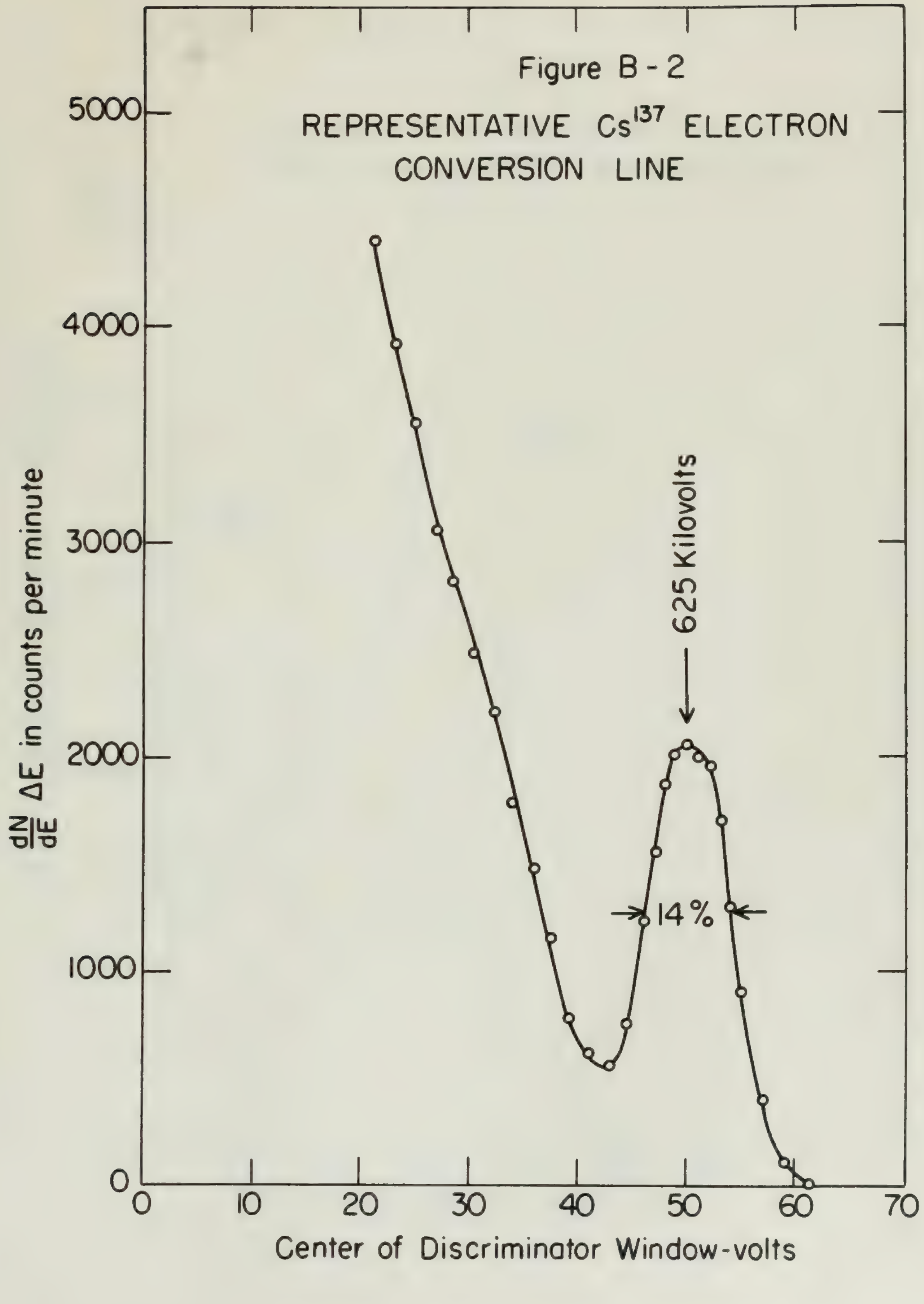


Figure B - 2

REPRESENTATIVE Cs^{137} ELECTRON CONVERSION LINE

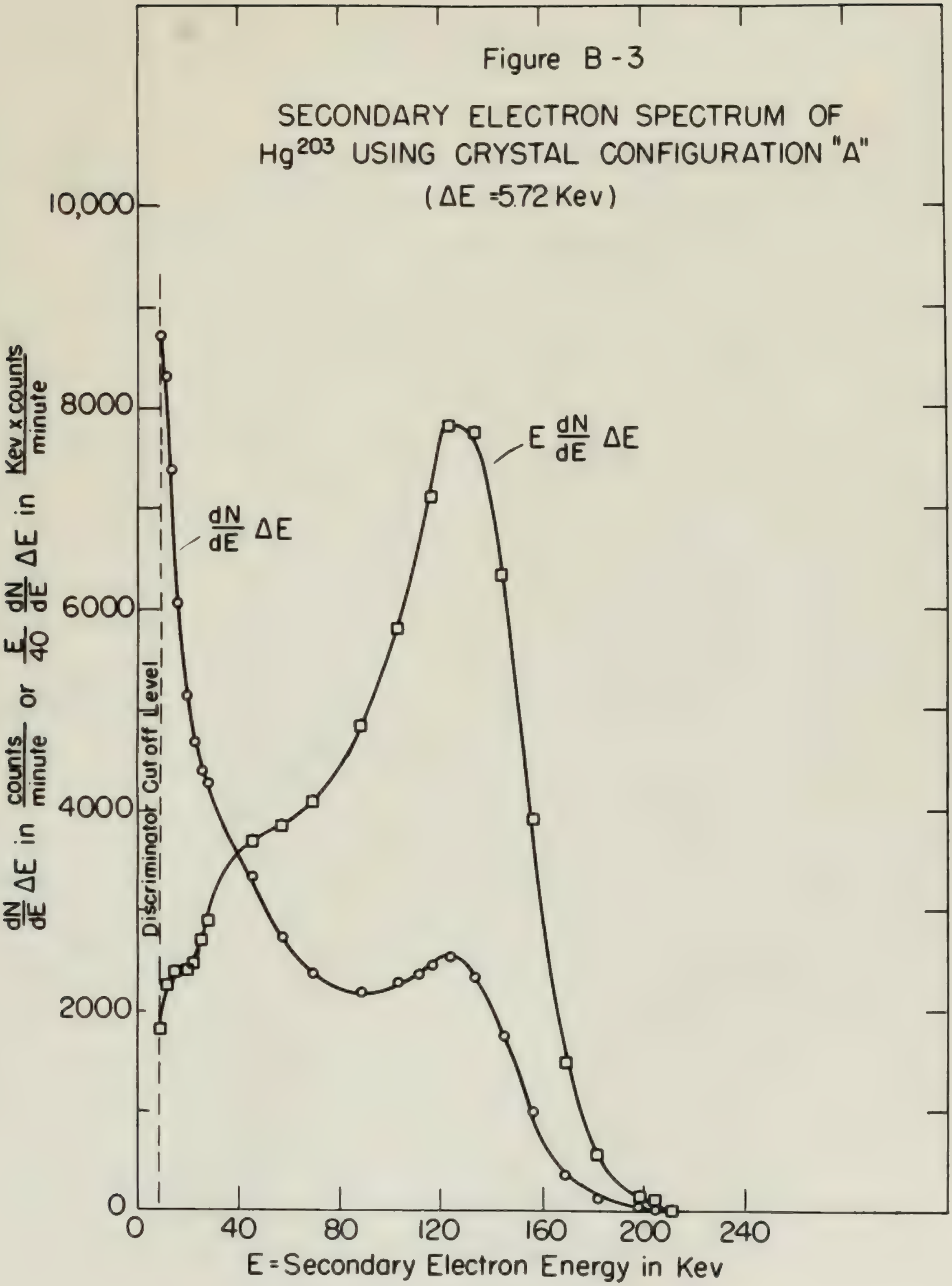


Figure B - 3

SECONDARY ELECTRON SPECTRUM OF Hg^{203} USING CRYSTAL CONFIGURATION "A"

(ΔE =5.72 Kev)

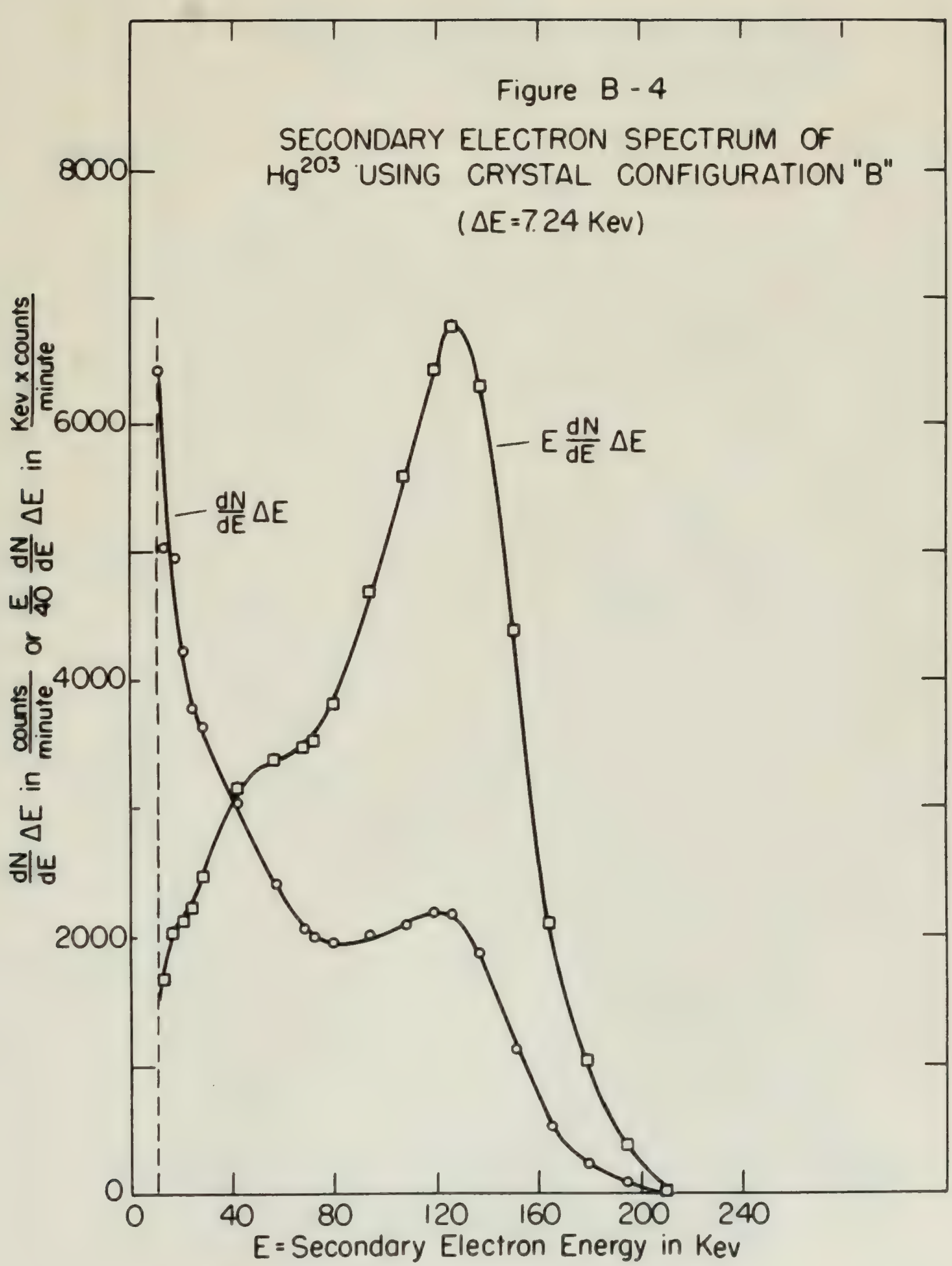


Figure B - 4

SECONDARY ELECTRON SPECTRUM OF Hg^{203} USING CRYSTAL CONFIGURATION "B"

($\Delta E = 7.24$ Kev)

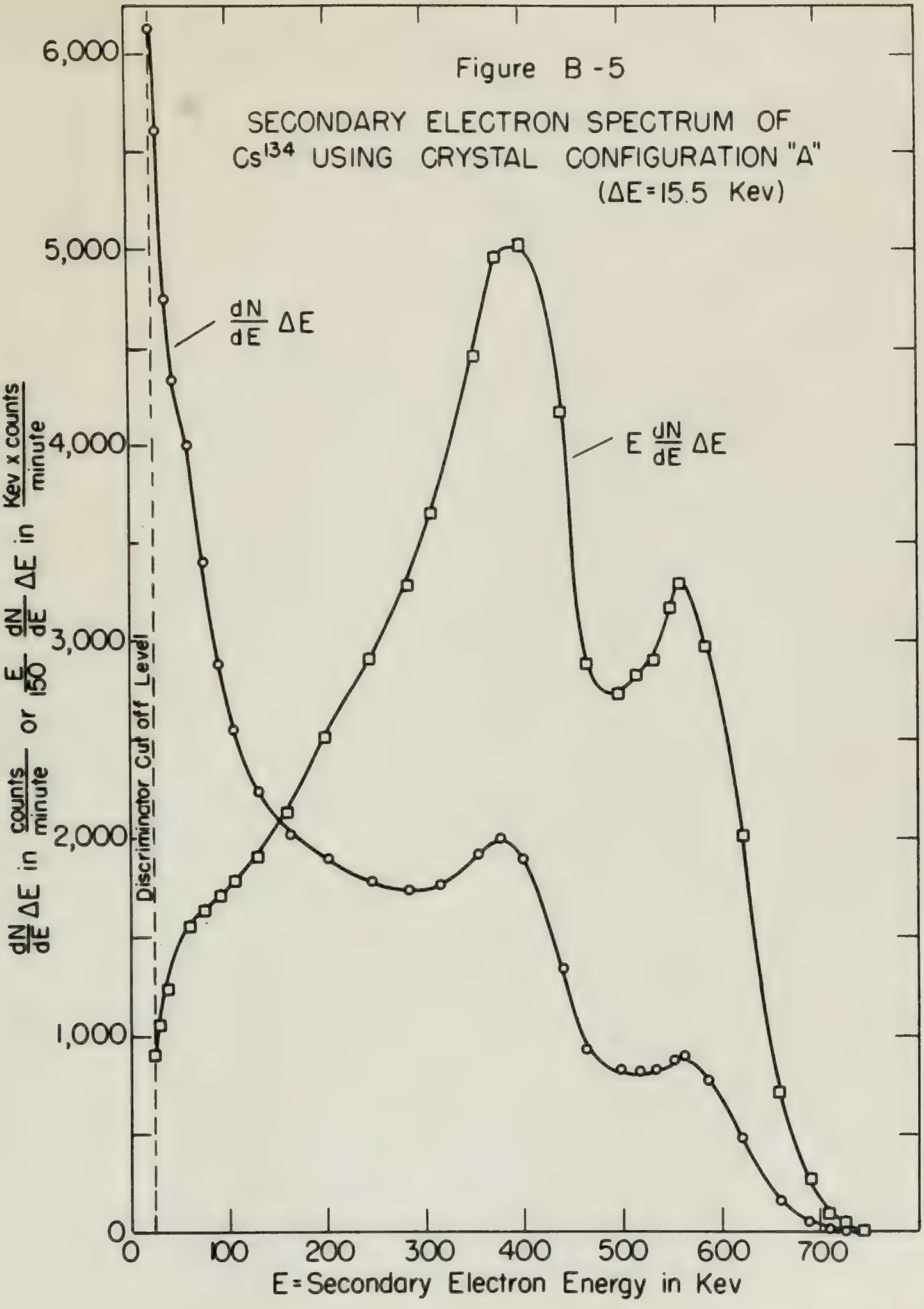


Figure B -5

SECONDARY ELECTRON SPECTRUM OF Cs^{134} USING CRYSTAL CONFIGURATION "A" (ΔE=15.5 Kev)

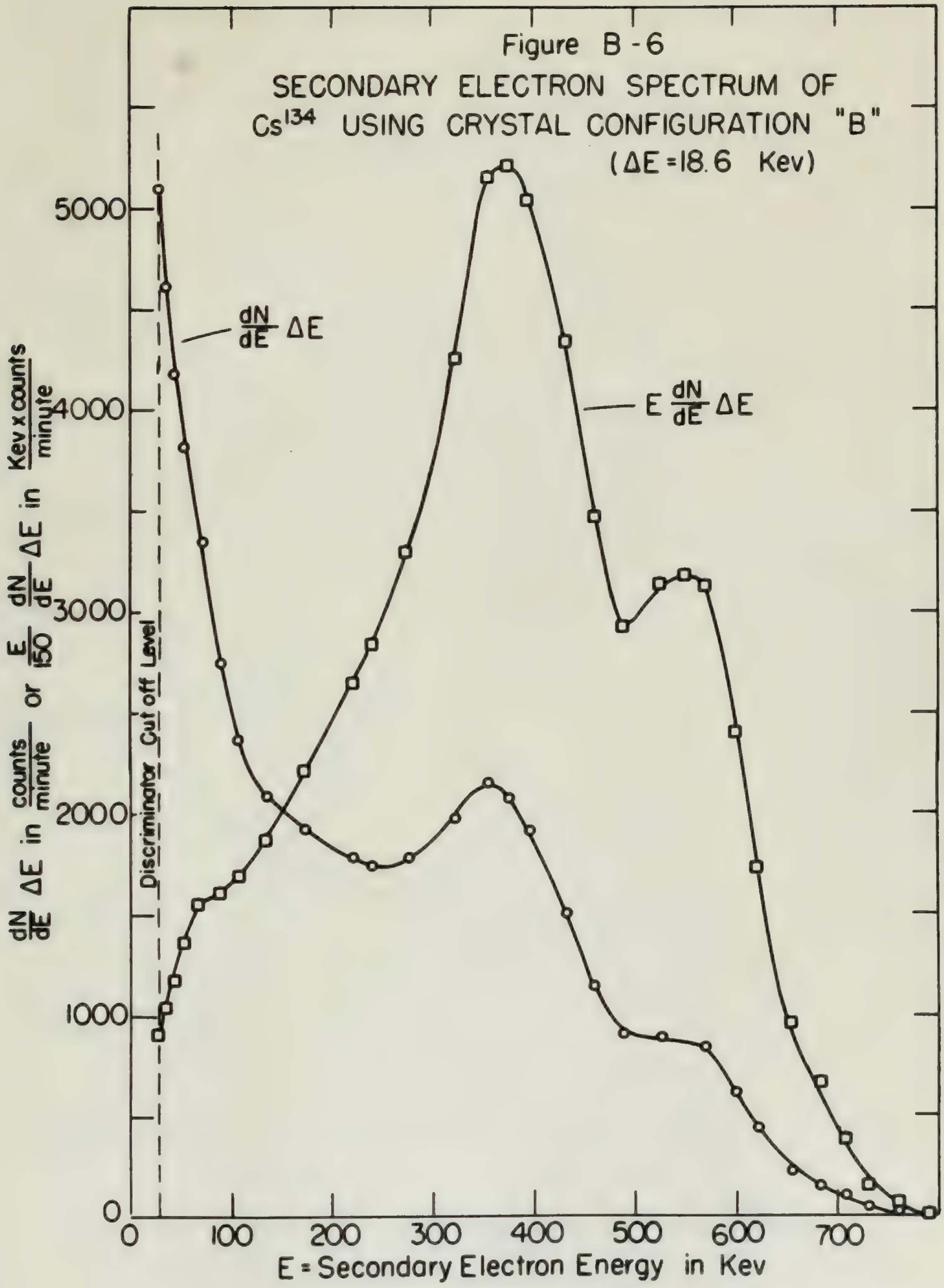


Figure B-6

SECONDARY ELECTRON SPECTRUM OF Cs^{134} USING CRYSTAL CONFIGURATION "B"

($\Delta E = 18.6$ Kev)

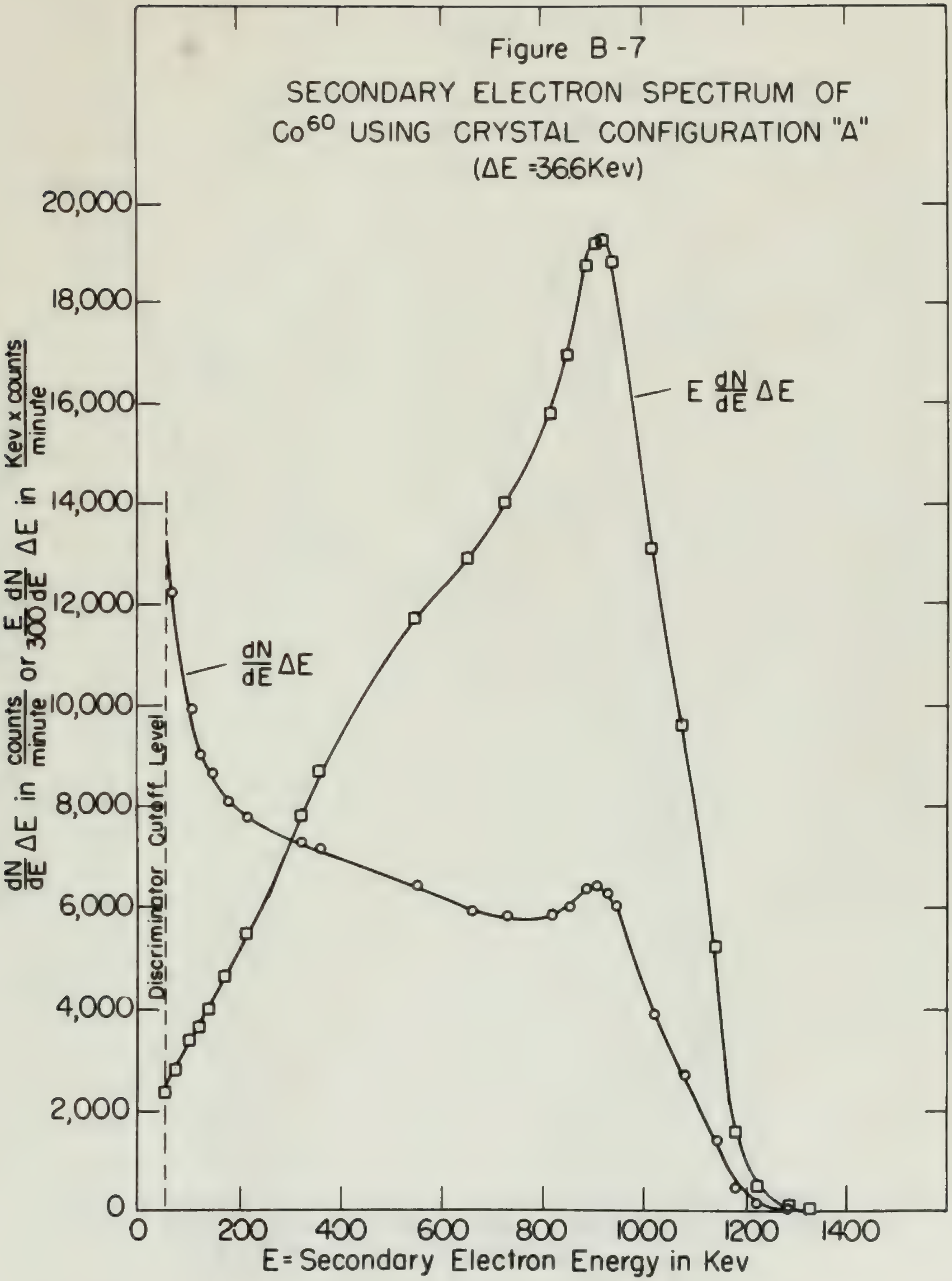


Figure B-7

SECONDARY ELECTRON SPECTRUM OF Co^{60} USING CRYSTAL CONFIGURATION "A"

(ΔE = 36.6 Kev)

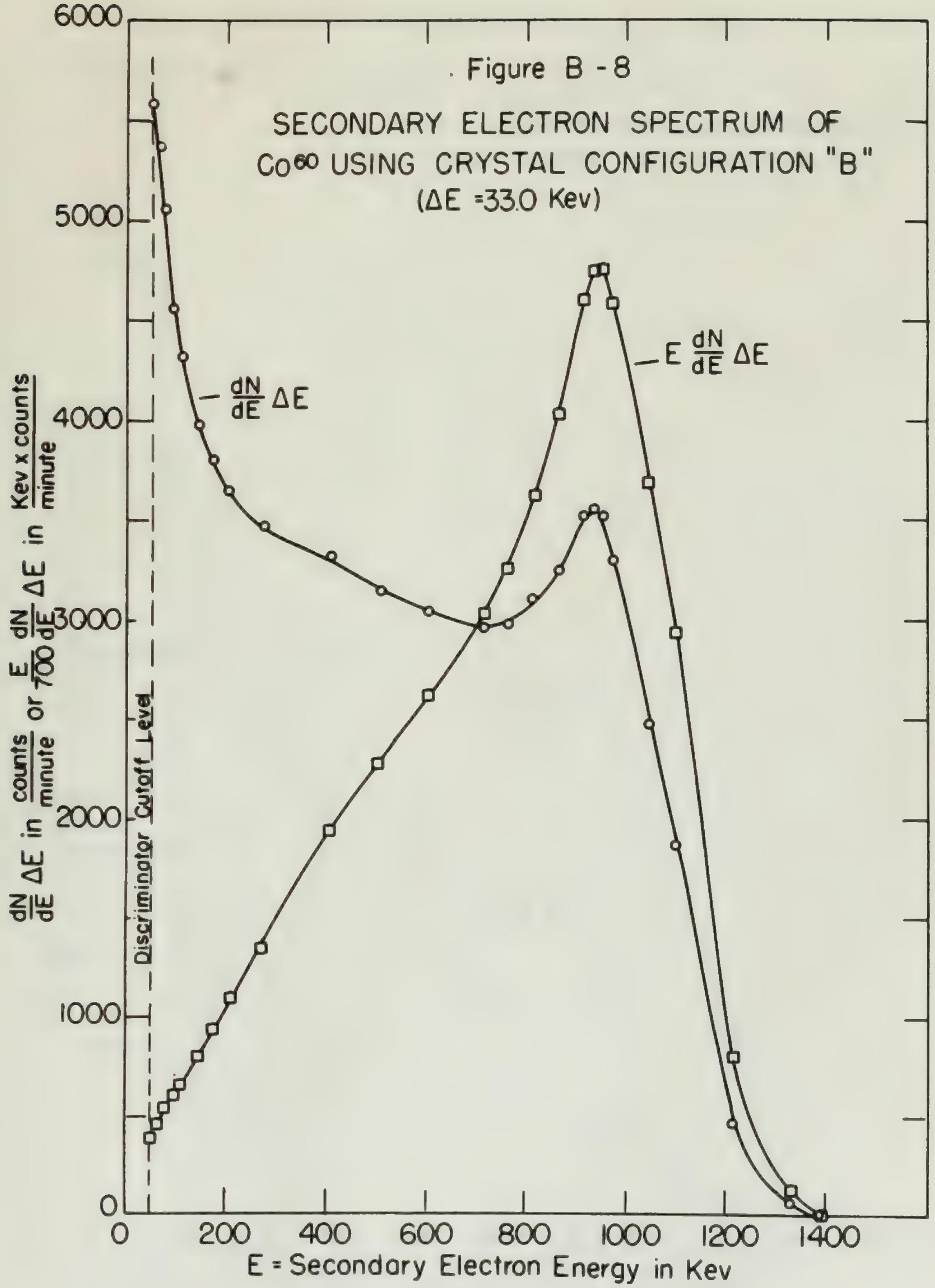


Figure B - 8

SECONDARY ELECTRON SPECTRUM OF Co^{60} USING CRYSTAL CONFIGURATION "B" (ΔE =33.0 Kev)

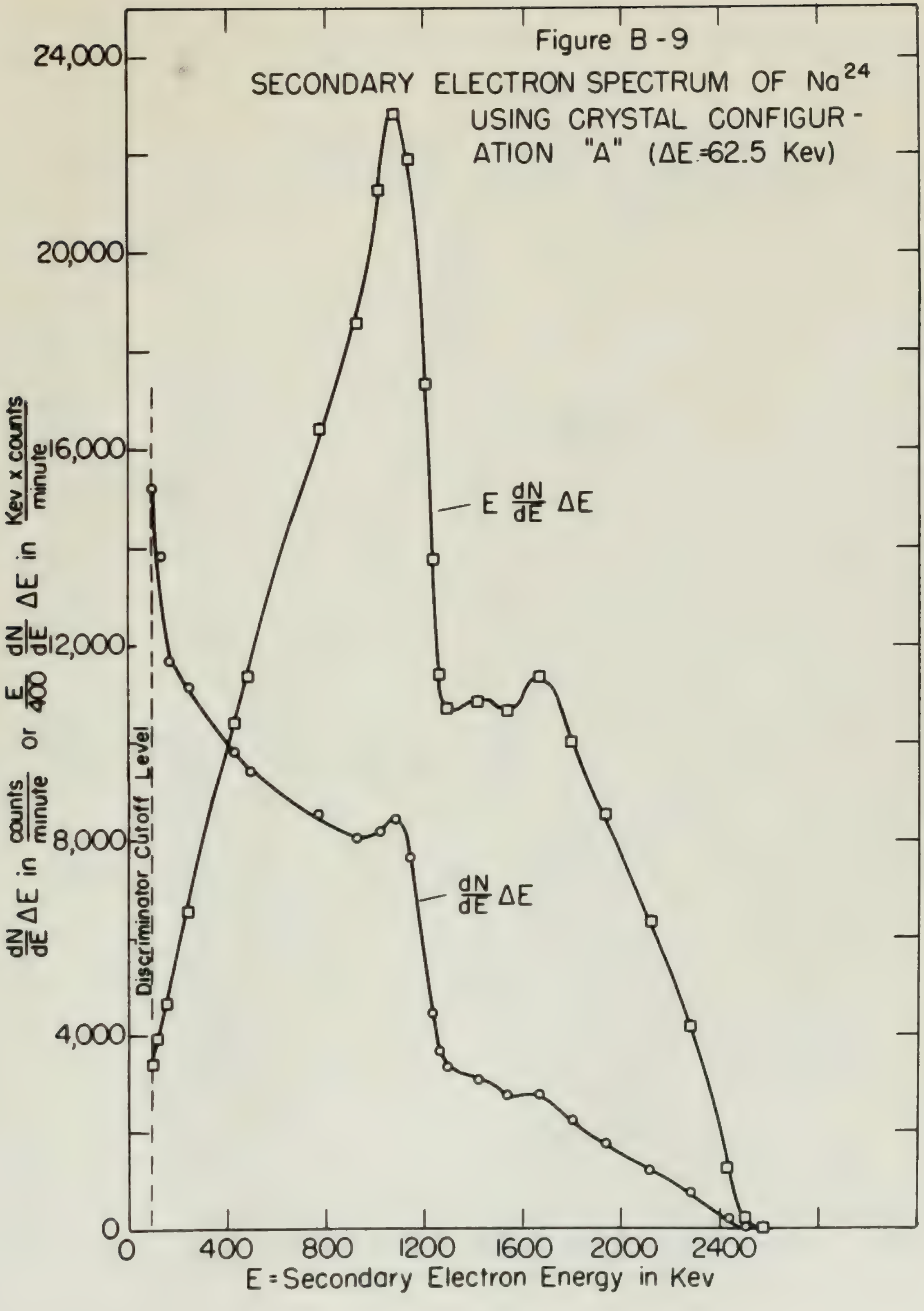


Figure B-9

SECONDARY ELECTRON SPECTRUM OF Na^{24} USING CRYSTAL CONFIGURATION "A" ($\Delta E = 62.5$ Kev)

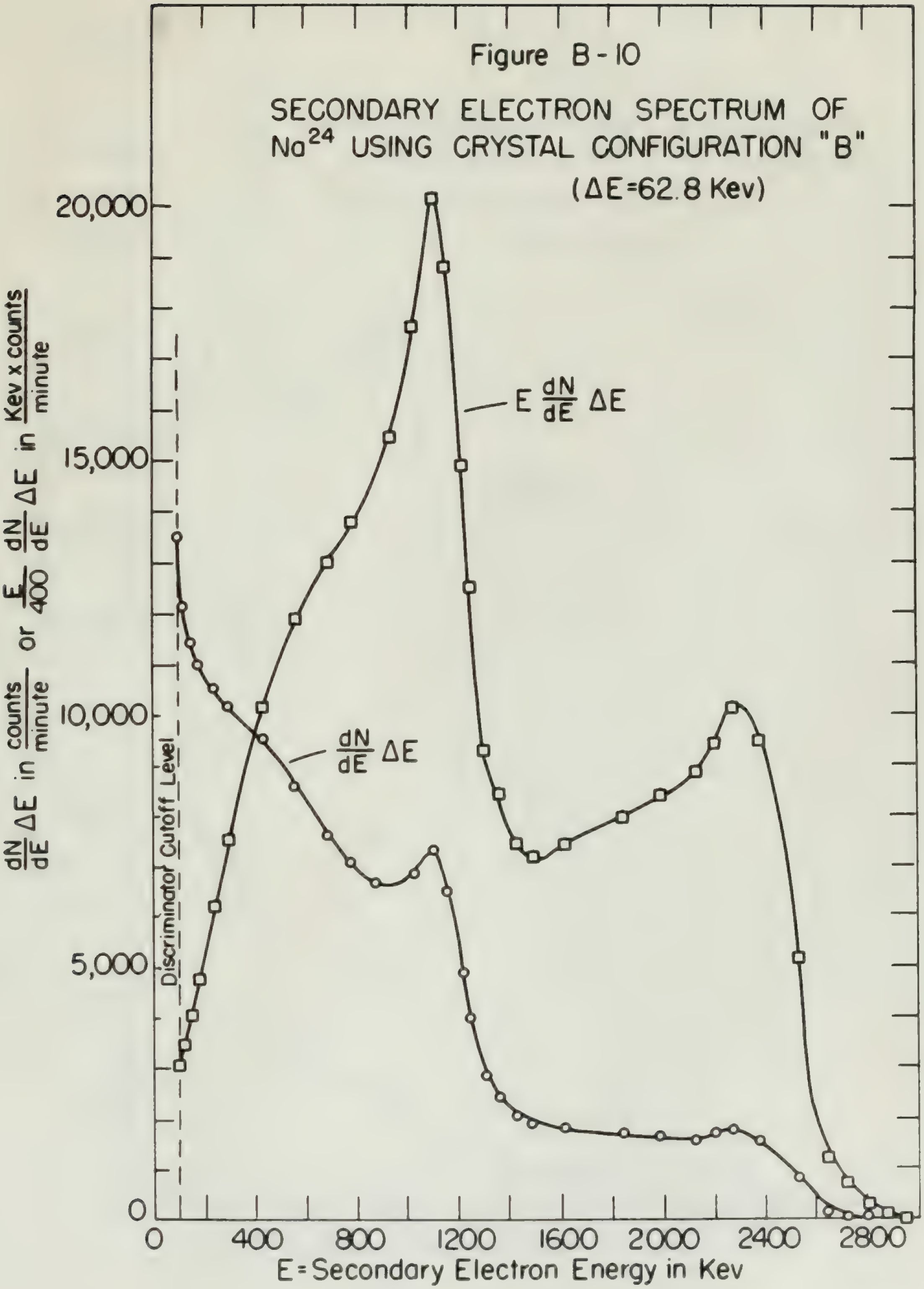


Figure B-10

SECONDARY ELECTRON SPECTRUM OF Na^{24} USING CRYSTAL CONFIGURATION "B"

(ΔE=62.8 Kev)

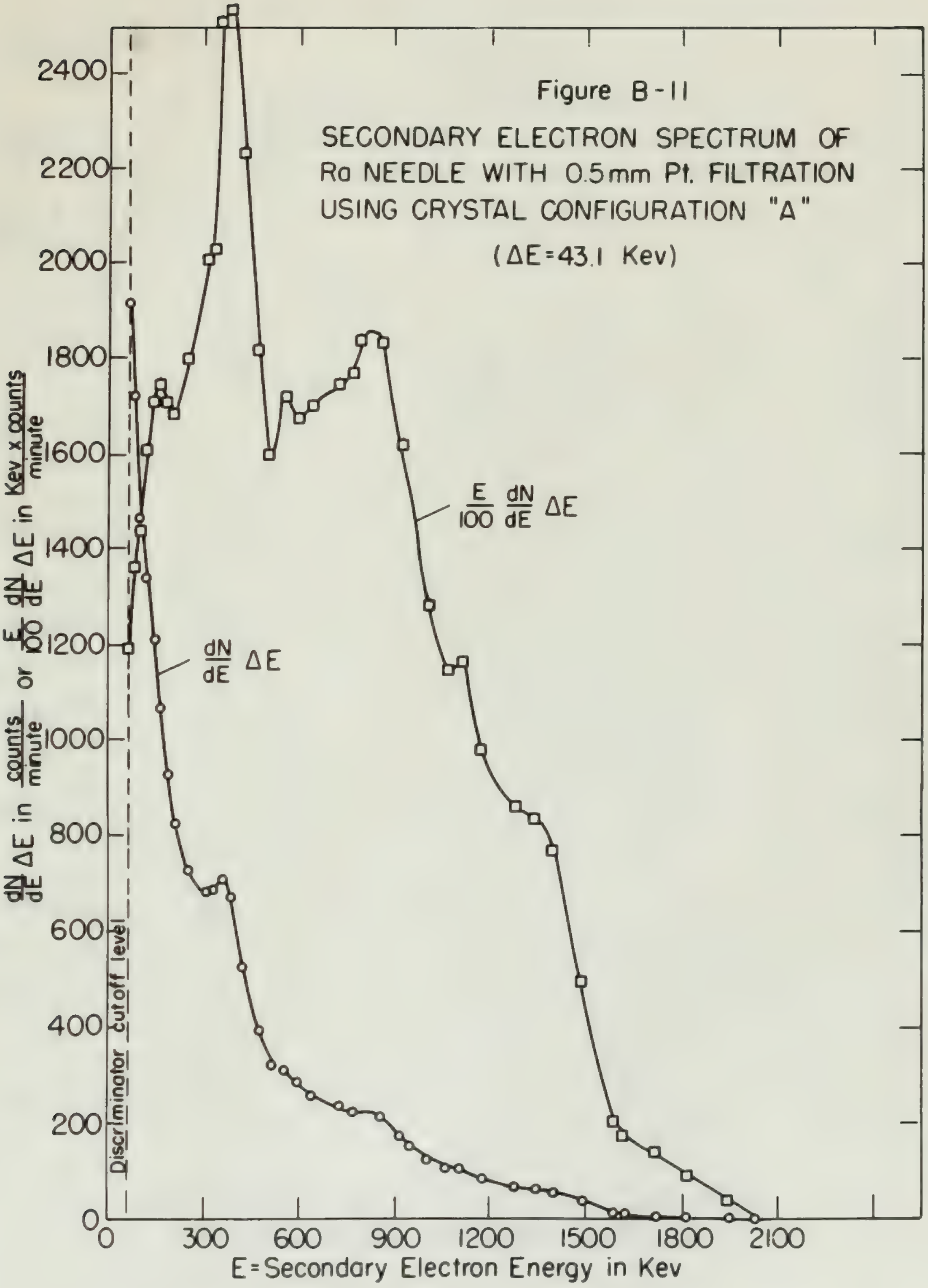


Figure B-11

SECONDARY ELECTRON SPECTRUM OF Ra NEEDLE WITH 0.5 mm Pt. FILTRATION USING CRYSTAL CONFIGURATION "A"

(ΔE=43.1 Kev)

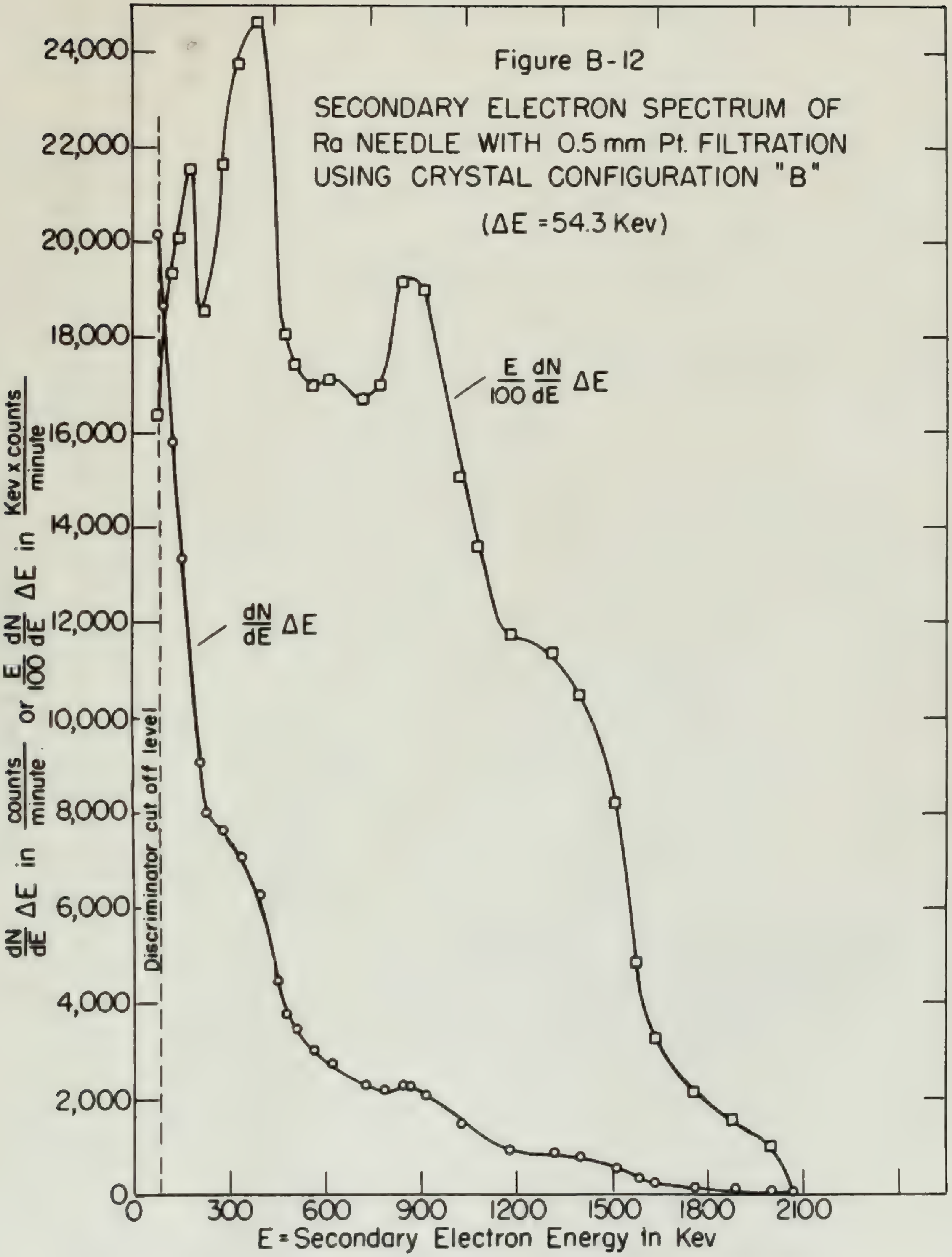


Figure B-12

SECONDARY ELECTRON SPECTRUM OF Ra NEEDLE WITH 0.5 mm Pt. FILTRATION USING CRYSTAL CONFIGURATION "B"

($\Delta E = 54.3$ Kev)

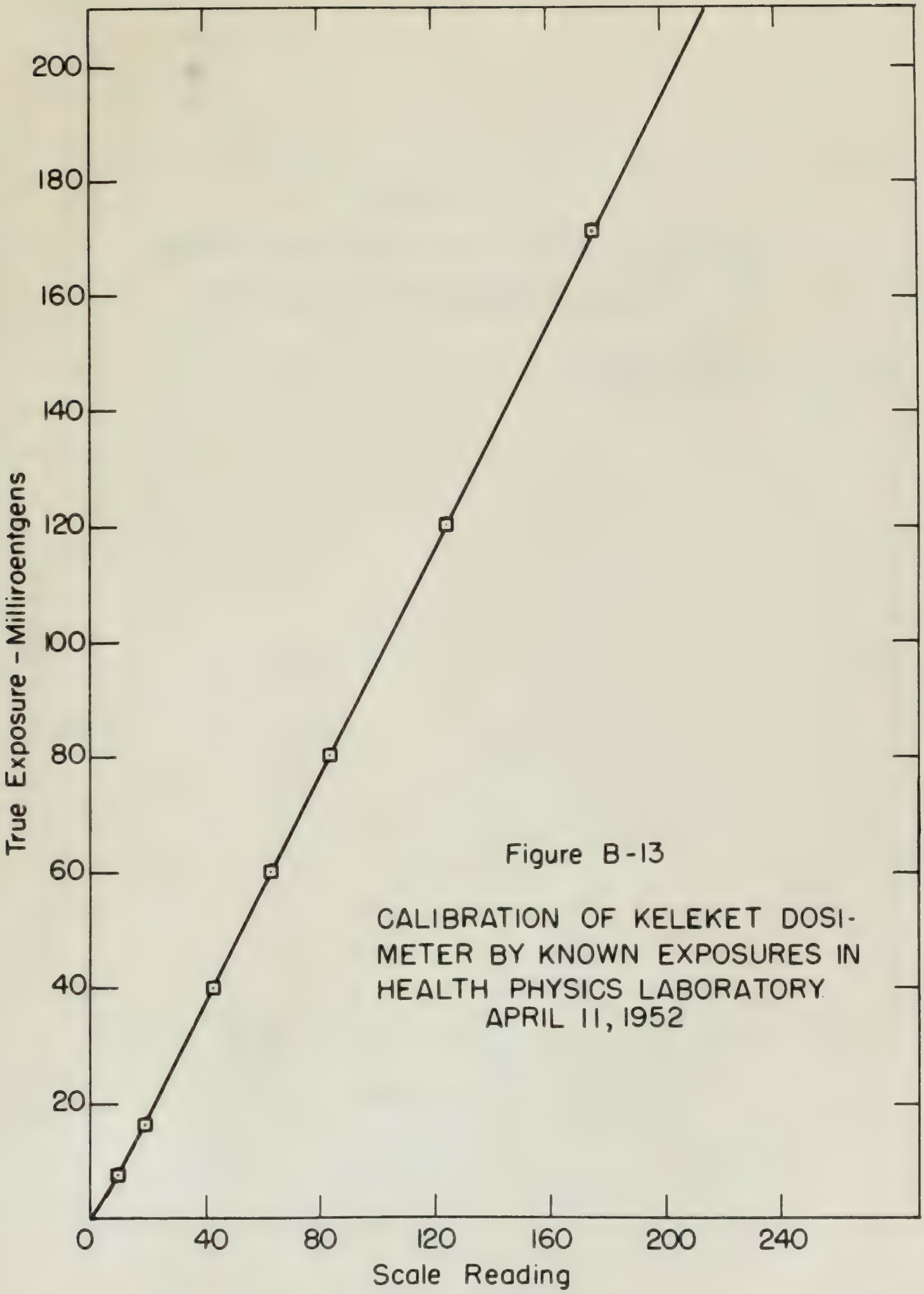


Figure B-13

CALIBRATION OF KELEKET DOSIMETER BY KNOWN EXPOSURES IN HEALTH PHYSICS LABORATORY
APRIL 11, 1952

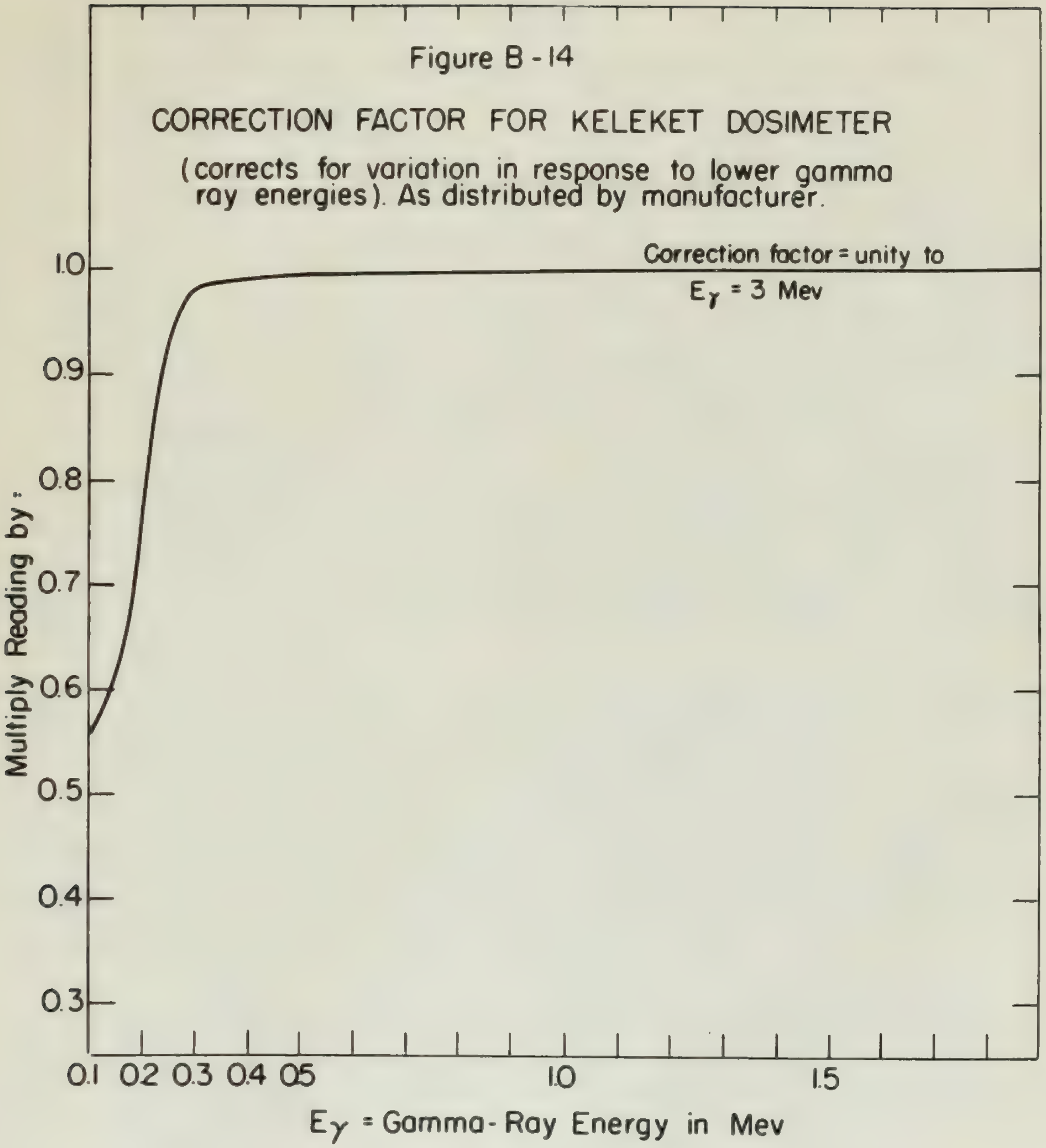


Figure B-14

CORRECTION FACTOR FOR KELEKET DOSIMETER

(corrects for variation in response to lower gamma ray energies). As distributed by manufacturer.

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